Implementation Issues for Departure Planning Systems

Proposal Submitted by the

International Center for Air Transportation
Massachusetts Institute of Technology

NCC 2-1147

Objective

The objective of the proposed effort is to investigate issues associated with the design and implementation of decision aiding tools to assist in improving the departure process at congested airports. This effort follows a preliminary investigation of potential Departure Planning approaches and strategies, which identified potential benefits in departure efficiency, and also in reducing the environmental impact of aircraft in the departure queue. The preliminary study bas based, in large part, on observations and analysis of departure processes at Boston, Logan airport. The objective of this follow-on effort is to address key implementation issues and to expand the observational base to include airports with different constraints and traffic demand.

Specifically, the objectives of this research are to:

- Expand the observational base to include airports with different underlying operational dynamics.

- Develop prototype decision aiding algorithms/approaches and assess potential benefits.

- Investigate Human Machine Integration (HMI) issues associated with decision aids in tower environments.

Background

The "departure process" has been identified as one of the key areas where inefficiencies and delays manifest in the current ATM system. For example, in a 1994 ATA study, taxi delays were estimated to account for $1.57B annually or 44% of the total losses. While it is important to note that the cause of much of the taxi delay occurs from processes, which occur off the airport surface, the departure process is an important area for potential improvement. This is supported by preliminary AATT benefits analysis, which identify improvement to the departure process as having high value.

While the development of decision aiding tools for the arrival process has made significant progress in recent years (e.g. CTAS, TMA) the development of decision aiding tools for the departure process is still relatively undeveloped although some efforts such as SMA and SMS have begun to move in this direction. This is, in part, due to the complexity of the departure process, the fact that many of the inefficiencies which manifest on the surface are not directly controllable by ATC and human interface issues associated with providing decision aiding tools to controllers who rely heavily on "out the window" visual monitoring.

In 1997 an initial effort to investigate departure planning at congested airports was initiated by the MIT International Center for Air Transportation with the support of NASA. The approach taken to develop departure-planning tools was to first carefully observe departure processes at congested airports and to identify key flow constraints (i.e. "identify the plant"). For practical and logistical reasons the prime airport for observation was Boston Logan airport (BOS) although field observations were made at other airports (ATL, DFW, ORD, Memphis). Data analysis was conducted at BOS and other airports using ASQP data as well as other data sources such as airline internal delay reports. Preliminary results of these observations are included in Appendices A and B. In general the airport departure process was identified as an interactive queuing processes with downstream constraints sometime back-propagating to the airport surface. The runways were identified as the key flow constraint and the runway departure queue was identified as a major inefficiency in the process. Other important constraints were gates, departure flow restrictions, controller workload and limitations from airport geometry and taxiway layout.

Based on the observational results, analysis of potential control strategies and potential objective functions for departure planning tools were investigated. One objective, which emerged, in addition to improving departure flow rates, was the potential to reduce aircraft emissions on the surface by reducing unnecessary time in the runway departure queue.

A preliminary architecture for a departure-planning tool was developed and several control approaches were identified. Initial development and analysis of several control strategies was started. One simple approach (N control) was to limit the number of departing aircraft taxiing in order to maximize and maintain pressure on the departure runway without building excessive departure queues. (Appendix C) While the "N Control" approach appears promising there are significant implementation issues such as availability of gates and airline acceptability, which must be addressed. Other more sophisticated approaches were identified including a "virtual queue" approach to manage both the timing and the order of the departure process towards a specified target queue. However, significant issues remain as to what would define an "optimal" virtual queue and algorithmic issues as to how such an "optimal virtual queue" would be generated.

An additional issue, which emerged from observations and interviews with tower controllers, is the Human Machine Interface (HMI) between the controllers and any Decision Planning Tool. Most of the positions in Tower operations require significant "heads up" attention where the controller is spending most of his/her visual resources monitoring the external visual scene. While there are some internal Tower displays (e.g. BRITE display) the controllers are reticent to use any tool which will significantly increase their heads down time. The controllers were observed to have a heavy reliance on flight progress "strips" both as a surrogate for tracking the dynamics of the flows within the airport but also as a communication mechanism both between controllers and between the controllers and the "system" (i.e. host computer).

Due to the ability to manipulate strips controllers are able to read, annotate and monitor the strips while still maintain external visual scan. In field observations at ATL where barcode tracking is used to record the movement of strips between control positions, controllers were observed to be able to scan the strips as part of their normal strip handling process without difficulty. This indicates that an "Active Flight Strip"(AFS) may be a promising approach to the interface between tower controllers and decision aids such as a departure planner. Conceptually, an AFS is a palm size computer with the form factor of the current flight strip holder. The AFS would allow handwritten controller input and perhaps discrete button inputs. The AFS would have the capability of automatically locating and communicating its position within the tower cab, as well as wireless data communication to a local or host server.

The results from the initial study of Departure Planning coupled with the significant potential for operational and environmental benefits indicate that the Departure Planning concept should be developed further. The proposed effort focuses on key implementation issues including the development of prototype decision aiding algorithms and Human Machine Interface issues. In addition, the insight gained from the detailed observations at BOS indicates that there is value in continuing the observations at BOS and expanding the observational base to include airports with different underlying operational dynamics.

Description of the Research

The proposed research will address the following:

1. Expand the Observational Base to Include Airports with Different Underlying Operational Dynamics.

Data collection and analysis will support the team's effort at building new decision aiding algorithms, assess potential benefits and investigate Human-Machine Integration issues associated with the implementation of these algorithms. Under this task, candidate airports will be chosen, on-site observations will be performed and statistically significant data will be collected and analyzed.

- *Choosing new observation sites*

Preliminary investigations have shown that airport dynamics and critical flow constraints tend to vary from airport to airport. We therefore propose not only to perform additional observations at Logan Airport but also to initiate observations at other airports as well. Observations at Logan airport will build upon the significant knowledge already gathered about current operations and prototype departure planning tools to investigate in detail Human Machine Interface issues associated with tool implementation (described thereafter). Observations at other sites will primarily be done to identify those dynamics and constraints that may not be observed well at Logan, including significant hub operations, airline/airport collaborative decision making and glaring airport operational inefficiencies. Initial candidates could include Philadelphia, Newark and Atlanta Hartsfield. Indeed, Philadelphia airport offers an interesting profile because, although its infrastructure appears to be similar to that of Logan Airport, its operations are those of a hub airport. In addition, this airport is subject to significant post-departure constraints, because of its location close to New-York terminal operations. Newark is a very busy hub airport, for which preliminary analyses have shown the biggest potential environmental and cost savings so far (see Appendix D). In conjunction with Philadelphia, it would also allow the team to study post-departure coupling effects among neighboring airports and their possible back propagation to the departure process itself. Finally, preliminary on-site investigations indicate that Atlanta Hartsfield Airport may be the location for significant ramp management and airline/tower collaborative decision making issues. Previous experience with on-site investigations indicates that at most two airports should be investigated simultaneously. Selection of field sites will be made in collaboration with NASA to best meet the combined objectives of this study and other NASA programs.

- *On-site observations.*

Under this task, the main decision centers of the chosen airport(s) will be visited by faculty members and qualified students. This task will involve recording, manually or automatically, the essential components of the decision processes taking place at the selected airports. These on-site observations are critical to the identification of those airport dynamics and constraints for which little or no archived data are readily available. These include the detailed human organization of the control tower and the airline ramp tower, the implicit decision rules and strategies followed by human operators and not recorded in standard operating procedures documents and the path followed by flight strips during the departure process. A significant benefit of on-site observations is the ability to interview (when appropriate) or collect input from operators. This supports determination of those issues that are central to the proper operation of the airport under consideration, such as airport layout constraints, special departure procedures and their causes and downstream constraints in case of backpropagation of airspace congestion down to the ground. Current approaches to departure runway balancing will also be considered under this task.

While most on-site observations have concentrated on the control tower so far, observations at airports with a strong hub-and-spoke structure may also include ramp towers. In that case, significant insight could be gained about airport dynamics by observing gate turnaround dynamics, causes for gate congestion, ramp operations during the departure process, and the transfer of control from the ramp tower to the airport tower. New observations will also investigate internal airline lead information on departure time based on several variables such as cargo loading, catering and passenger boarding information.

- *Archived data collection and analysis.*

Public data are available for all major airports in the United States. These include the Airport Service Quality Program (ASQP) data, the Consolidated Operations and Delay Analysis System, as well as other files such as weather and airport configuration files. These data complement on-site observations by offering a coarser, but statistically significant set of airport observations. These have been so far critical to establishing cost-benefit analyses for specific airport departure management approaches and we expect this to be still true for future investigations. New data acquisition efforts could include radar track data to provide statistically significant information about the relationship between the departure process and downstream constraints, such as miles-in-trail constraints, as well as the "controllability" of the airborne phase of the flight from the ground. It could also provide, in cooperation with NASA's own efforts, significant information about the dynamics of coupled departure-arrival operations, to be used in subsequent algorithm developments.

2. *Develop Prototype Decision Aiding Algorithms/Approaches and Assess Potential Benefits.*

Although a generic architecture for the Departure Planner (DP) has been proposed, specific implementation issues such as the relative authority of specific DP components and their interactions with other automation tools have not been addressed in detail. In this task, the details of the DP architecture will be developed and the benefits of the DP will be determined through data and engineering analysis where appropriate. Previous work indicates that the DP architecture will encompass both strategic and tactical objectives.

At the strategic level, the DP must interact with the other automation tools that are used to manage the arrival demand at airports. Tools and protocols such as the Ground Delay Program (GDP) and Traffic Movement Advisor (TMA) are used by airlines and air traffic flow management to determine and manage the arrival demand. The DP must be aware of the current and projected demand so that it can respond appropriately to demand changes and thus the opportunities for departures. Implementation issues such as the relative time scales, controllability and relative levels of control of the DP, GDP and TMA for example, will be investigated and a prototype architecture will be developed based on the results of this study.

At the tactical level, three control strategies have been identified as possible solutions to the need for ground movement control: (a) N-Control, (b) N-Control + Sequencing and (c) Time Based Virtual Queue. These control strategies represent the spectrum of possible control algorithms.

The N-Control strategy is the simplest of the three tactical strategies and is currently envisioned to require no significant changes in ground control from the perspective of Air Traffic Control (ATC). In this strategy, ATC is required to monitor the number of aircraft taxing out and either allow a pushback if the number of aircraft taxiing out is less than a pre-determined "optimum" for a given runway configuration or hold a pushback if that pushback will cause the number of aircraft taxing out to be greater than the desired number. This strategy will require gate holding and thus might impact airline operations. The impact on airline operations may be mitigated by improved coordination between ATC and the airlines through collaborative decision making. This coordination will require the efficient exchange of information between ATC and the airlines. The Surface Movement System (SMS) and Collaborative Arrival Planner (CAP), information infrastructure and automation tools currently under development and field study, are likely points of interaction between the DP and other automation tools. The effect of the N Control strategy on airline operations and implementation issues such as the appropriate architecture for the interaction between ATC and the airlines will be investigated in this task, and an architecture will be proposed.

The N-Control + Sequencing strategy enhances the simple N-Control strategy through the addition of position swapping in the departure sequence to address capacity reducing constraints such as wake vortex and miles in trail restrictions. This represents a "hybrid" control strategy as it combines the reduced queuing (and thus environmental and fuel burn benefits) of N-Control with the capacity enhancements that will result from consideration of capacity constraints in the departure sequence. In this approach, aircraft that have made pushback requests or are highly likely to make pushback requests within a "time window" will be sequenced based on the restrictions in effect at the time. Issues such as the size of the time window, the frequency with which the sequencing will be performed and the optimality of the solution will be addressed. Preliminary analysis suggests that dynamic programming and/or heuristic based control laws would be appropriate. In this task, the relative strengths and weakness of these control laws will be studied and the results will be used to develop a control architecture. The benefits of the architecture will be determined.

The Time Based Virtual Queue strategy is the most computationally rigorous tactical control strategy and involves the detailed scheduling of aircraft movement based on a virtual queue that maintains a sequence of departures that includes aircraft that have not yet pushed back from the gate. Critical implementation issues include the effect of the observed high uncertainty in pushback and taxi times on the size of the time window and frequency over which the algorithm may be used, and the ability to achieve optimality. A study of these issues will form the basis of a proposed architecture.

3. *Investigate Human Machine Integration (HMI) Issues Associated With Decision Aids In Tower Environments.*

This task will investigate HMI issues associated with decision aids in tower environments. The first phase of the task will involve the definition of functional requirements for potential decision aiding systems and the identification of key human factors and operational concerns. This will be accomplished by a task and input/output analysis of various controller positions. The analysis will be supported by field observations of tower facilities (coupled with the efforts in Task 1) as well as surveys and focused interviews conducted with tower personnel (if available).

In parallel with the development of functional requirements, a technical feasibility analysis will be conducted to identify potential candidate approaches, which may be considered for Tower HMI applications. These are expected to include: head down displays, active flight strips, reflected HUD, movable flat panels and voice based systems. Technical issues to be addressed include special limitations involved in the tower environment (e.g. RFI concerns and sunlight readability) as well as processor issues, communications link, data architecture, etc.

Based on the results of the functional requirement and the technology feasibility study, one or more systems will be selected for preliminary prototyping in the second phase. The prototype systems will undergo preliminary HMI evaluation in a laboratory environment and after refinement will be evaluated in either a tower environment or the NASA tower simulation system if the facility is available and the experimental protocol is appropriate.

The third phase of the task will be to test and evaluate the most promising approach with a prototype Departure Planner system in either a real or simulated environment.

Research Plan

FY '00

The following specific objectives shall be accomplished:

(a) Conduct field observations. Determine, in cooperation with NASA, a new airport for on-site investigations. Initiate observations and data collection. Continue observations at Logan airport towards supporting HMI study.

(b) Development of preliminary DP algorithms and assessment of benefits. Preliminary efforts will concentrate on the N Control and Sequencing approaches.

(c) Conduct functional requirement analysis, technical annuluses and preliminary design of Tower HMI approaches.

FY '01

The following specific objectives shall be accomplished:

(a) Continue field observations, concentrating on non-Logan airport. Investigate airport-specific dynamics and constraints to support development of new algorithms and cost-benefit analyses.

(b) Continued development of DP algorithms and addressing key issues, which emerge in the development of multi-objective, hybrid optimization schemes.

(c) Development and preliminary testing of prototype Tower HMI devices.

FY '02

The following specific objectives shall be accomplished:

(a) Conclude field observations. Emphasize human factors issues arising at new airport to study needs for adaptation or development of man-machine interfaces.

(b) Assessment of preliminary DP control algorithms and prototype application to one or more case study airports. Preliminary development of advanced algorithmic approaches such as Time Based Virtual Queue.

(c) Refinement of prototype Tower HMI devices. Test and evaluation of Tower HMI devices interfaced with prototype Departure Planner algorithms in simulated or operational environment as appropriate.

Reporting Requirements

1. Progress update reports will be submitted on a semi-annual basis.
2. A full written report will be submitted at the end of each fiscal year.
2. Briefings and presentations will be provided to the NASA technical monitor on an occasional basis, as requested.
3. The results of this research will be reported in appropriate conferences and archival research journals.

Research Team

The research team will be led by Professor R. John Hansman as Principal Investigator and by Professors Eric Feron and John-Paul Clarke as Co-Principal Investigators. Professor Amedeo Odoni will also participate as a Co-Principal investigator but will be on sabbatical for the 99/00 academic year. All four are on the faculty of the Department of Aeronautics and Astronautics at MIT and all are associated with the International Center for Air Transportation (ICAT) which Professor Hansman directs, and with the National Center for Excellence in Aviation Operations Research (NEXTOR). It is expected that an average of three graduate students at the Ph.D. or Master's level will be supported as full-time graduate research assistants throughout the duration of the research project. These students will prepare their Ph.D. dissertation or Master's thesis in connection with the research project.

Proposed Project Duration

September 1, 1999 – August 31, 2002

Budget Summary

From September 1, 1999 to August 31, 2000

		NASA USE ONLY	
	A	B	C
1. Direct Labor (salaries, wages, and fringe benefits)	106,239		
2. Other Direct Costs:			
a. Subcontracts	0		
b. Consultants	0		
c. Equipment	0		
d. Supplies	1,200		
e. Travel	20,946		
f. Other	28,925		
3. Indirect Costs	83,223		
4. Other Applicable Costs	0		
5. Sub-total — Estimated Costs	240,533		
6. Less Proposed Cost Sharing (if any)	0		
7. Carryover Funds (if any)			
a. Anticipated Amount 0			
b. Amount used to reduce budget	0		
8. Total Estimated Costs	240,533		XXXXXXX
APPROVED BUDGET	XXXXXXX	XXXXXXX	

Instructions

1. Provide a separate budget summary sheet for each year of the proposed research.

2. Grantee estimated costs should be entered in Column A. Columns B and C are for NASA use only. Column C represents the approved grant budget.

3. Provide in attachments to the budget summary the detailed computations of estimates in each cost category, along with any narrative explanation required to fully explain proposed costs.

------------------------ ADDITIONAL INSTRUCTIONS ON REVERSE ------------------------

Budget Summary

From September 1, 2000 to August 31, 2001

	A	B NASA USE ONLY	C
1. Direct Labor (salaries, wages, and fringe benefits)	110,325		
2. Other Direct Costs:			
a. Subcontracts	0		
b. Consultants	0		
c. Equipment	0		
d. Supplies	1,200		
e. Travel	20,946		
f. Other	30,290		
3. Indirect Costs	86,953		
4. Other Applicable Costs	0		
5. Sub-total — Estimated Costs	249,714		
6. Less Proposed Cost Sharing (if any)	0		
7. Carryover Funds (if any)			
a. Anticipated Amount 0			
b. Amount used to reduce budget	0		
8. Total Estimated Costs	249,714		XXXXXXX
APPROVED BUDGET	XXXXXXX	XXXXXXX	

Instructions

1. Provide a separate budget summary sheet for each year of the proposed research.

2. Grantee estimated costs should be entered in Column A. Columns B and C are for NASA use only. Column C represents the approved grant budget.

3. Provide in attachments to the budget summary the detailed computations of estimates in each cost category, along with any narrative explanation required to fully explain proposed costs.

----------------------- ADDITIONAL INSTRUCTIONS ON REVERSE -----------------------

Budget Summary

From September 1, 2001 to August 31, 2002

		A	NASA USE ONLY B	C
1.	Direct Labor (salaries, wages, and fringe benefits)	114,619		
2.	Other Direct Costs:			
	a. Subcontracts	0		
	b. Consultants	0		
	c. Equipment	0		
	d. Supplies	1,200		
	e. Travel	20,946		
	f. Other	31,655		
3.	Indirect Costs	91,333		
4.	Other Applicable Costs	0		
5.	Sub-total — Estimated Costs	259,753		
6.	Less Proposed Cost Sharing (if any)	0		
7.	Carryover Funds (if any)			
	a. Anticipated Amount 0			
	b. Amount used to reduce budget	0		
8.	Total Estimated Costs	259,753		XXXXXXX
	APPROVED BUDGET	XXXXXXX	XXXXXXX	

Instructions

1. Provide a separate budget summary sheet for each year of the proposed research.

2. Grantee estimated costs should be entered in Column A. Columns B and C are for NASA use only. Column C represents the approved grant budget.

3. Provide in attachments to the budget summary the detailed computations of estimates in each cost category, along with any narrative explanation required to fully explain proposed costs.

------------------------ ADDITIONAL INSTRUCTIONS ON REVERSE ------------------------

PROPOSED COST ESTIMATE
9/1/99 — 8/31/02

	Year 1		Year 2		Year 3		Total	
	Person Mos.	Amount	Person Mos.	Amount	Person Mos.	Amount	Person Mos.	Amount
SALARIES & WAGES								
* Professor Clarke (AY)	0.00	-	0.00	-	0.00	-	0.00	0
Professor Clarke (Summer)	0.50	3,672	0.50	3,817	0.50	3,967	1.50	11,456
* Professor Feron (AY)	0.00	-	0.00	-	0.00	-	0.00	0
Professor Feron (Summer)	1.00	7,856	1.00	8,167	1.00	8,489	3.00	24,512
* Professor Hansman (AY)	0.00	-	0.00	-	0.00	-	0.00	0
Professor Hansman (Summer)	1.00	12,578	1.00	13,078	1.00	13,600	3.00	39,256
* Professor Odoni (AY)	0.00	-	0.00	-	0.00	-	0.00	0
Professor Odoni (Summer)	0.50	7,283	0.50	7,572	0.50	7,878	1.50	22,733
Res. Support Personnel	0.60	2,783	0.60	2,897	0.60	3,011	1.80	8,691
Res. Support Personnel	0.60	2,112	0.60	2,195	0.60	2,282	1.80	6,589
Research Assistant (PhD Candidate)	24.00	38,190	24.00	39,780	24.00	41,460	72.00	119,430
Research Assistant (SM Candidate)	12.00	17,265	12.00	17,940	12.00	18,660	36.00	53,865
Undergraduate Students (UROP)		5,000		5,000		5,000		15,000
TOTAL SALARIES & WAGES	40.20	96,739	40.20	100,446	40.20	104,347	120.60	301,532
EMPLOYEE BENEFITS @ 24.7% (excluding UROP & RAs)		8,962		9,319		9,689		27,970
VACATION ACCRUAL @ 11% (excluding Faculty, UROP & RAs)		538		560		583		1,681
OTHER COSTS								
Foreign Travel		3,490		3,490		3,490		10,470
Travel (Domestic)		17,456		17,456		17,456		52,368
Computation		1,800		1,800		1,800		5,400
Office/computer supplies, photocopies, telephone toll calls, and postage		1,200		1,200		1,200		3,600
Report Costs		875		875		875		2,625
** Research Assistant Tuition		26,250		27,615		28,980		82,845
TOTAL OTHER COSTS		51,071		52,436		53,801		157,308
TOTAL DIRECT COSTS		157,310		162,761		168,420		488,491
FACILITIES & ADMINISTRATIVE excluding Tuition & Equipment @ 63.5% @ 65.5% FY'02 and beyond		83,223		86,953		91,333		261,509
TOTAL		240,533		249,714		259,753		750,000

**MIT fully supports the academic year salary of Professors, Associate Professors and Assistant Professors, but makes no specific commitments of time or salary to any individual research project.*

**Beginning July 1, 1999, Research Assistant tuition in the summer has been subsidized for new and continuing graduate students in normal resident status during the preceding spring term who register only for thesis or pre-thesis research credit in the summer term.

Direct Labor

Number	Title	MM	Current Salary Base (*see note below*)	Salary Increase Effective
1	Faculty (*see note below*)	0.5	63,550 /9 month	July 1
1	Faculty (*see note below*)	1	68,000 /9 month	July 1
1	Faculty (*see note below*)	1	108,800 /9 month	July 1
1	Faculty (*see note below*)	0.5	126,100 /9 month	July 1
1	Research Support Personnel (*see note below*)	0.6	54,200 /year	January 1
1	Research Support Personnel (*see note below*)	0.6	41,550 /year	April 1
1	Research Assistant (PhD Cand)	24	1,575 /month	June 1
1	Research Assistant (SM Cand)	12	1,425 /month	June 1

Employee Benefits (UROP & RAs excluded) @ 24.7% FY 2000 and out years (*see note below*)
Vacation Accrual (excluding Faculty, UROP & RAs) @ 11% (*see note below*)

Other Costs

Computation: $50/month/person for use of International Center for Air Transporation (ICAT) Computer Facility.
Office supplies, xerox, telephone toll calls, and postage currently averages $100 per month based on past history
Report Costs--Page charges in a professional journal (based on AIAA rate of $875 per journal article)
Research Assistant Tuition: Full tuition is $25,000 for AY 1999-2000 of which 65% is subsidized by MIT (anticipated increase of 5%)

Equipment (value greater than $3,000)

list and explain the need of each piece over $3,000 otherwise
No items of equipment required

Travel

Destination:		West Coast	Washington, DC	TBA European City
	No. of People	1	1	1
	No. of days	3	1	3
	No. of Trips	10	2	2
Air Fare (full coach) @		1100.00	343.00	1315.00
Hotel (per day) @	$100	300.00	0.00	300.00
Food (per day) @	$35	105.00	35.00	105.00
Rental Car (per day) @	$45	135.00	0.00	0.00
Misc (taxi, tel calls, Parking, etc) @	$25	25.00	25.00	25.00
	Total per person trip	1665.00	403.00	1745.00
	Total	16650.00	806.00	3490.00

Facilities & Administrative @ 63.5% of total direct costs excluding tuition & equipment for MIT FY 2000 and FY 2001 @ 65.5% FY 2002 and out years

NOTES:

- Salary increases @ 4% rounded to nearest $100 and are current as of Aug-99
- MIT fully supports the academic year salary of Professors, Associate Professors and Assistant Professors, but makes no specific commitment of time or salary to any individual research project.
- Research Support Personnel is budgeted as an estimate of time required to provide clerical and administrative support for the P.I. as required for the performance of this project. Duties include but are not limited to the following: verifying payroll distribution, arrangement of travel relative to this project, submittal of appropriate forms to MIT purchasing, accounting, sponsored programs and other offices to meet regulatory, auditing and compliance requirements.
- Beginning July 1, 1999, Research Assistant tuition in the summer has been subsidized for new and continuing graduate students in normal resident status during the preceding spring term who register only for thesis or pre-thesis research credit in the summer term.
- Beginning Sept. 1, 1999, the subsidy of tuition and stipend changed from a 30% subsidy of both tuiton and stipend to a 65% subsidy of academic year tution and no subsidy of stipend.
- Vacation accrual, beginning July 1, 1998, has been removed from th EB rate and costs distributed only to those salary groups (Research, hourly and support staff) which are actually accrued. This charge will bear the prevailing Research F&A rate.

Preprint, 2nd USA/Europe ATM R&D Seminar, Orlando, FL, USA, December 1-4, 1998

Appendix A

OBSERVATIONS OF DEPARTURE PROCESSES AT LOGAN AIRPORT TO SUPPORT THE DEVELOPMENT OF DEPARTURE PLANNING TOOLS

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1 ABSTRACT

Field observations at Boston Logan International airport and data analyses comparing Logan to other major airports are conducted in order to identify the flow constraints that impede departure operations in an airport system. These observations and the associated analyses are discussed for each of the components of the airport system. It is concluded that the airport system is a complex interactive queuing system, that the different airport components contribute to cause delays and inefficiencies to different degrees, and that the runway system is the main flow constraint. The observations and analyses discussed reveal important implications for Departure Planning (DP) tools. The DP tools have competing objectives such as increasing the efficiency of the runway system, reducing delays and environmental impact, and maintaining acceptable workload levels and fairness. The interactions and dynamics between the different components of the airport system determine how and where in the system the DP tools can reduce the delays and inefficiencies most effectively. Important interactions between the DP tools and other decision-aiding tools such as CTAS and SMA are also discussed.

2 INTRODUCTION

The Departure Planner (DP) is a concept for a decision-aiding tool that would help improve the departure operations performance at major congested airports. In order to achieve this goal one needs first to identify the constraints in the system primarily responsible for generating inefficiencies and delays. Once these primary constraints are identified, one needs to understand the dynamics of the system in order to determine where and how the system operations could be adjusted to mitigate the inefficiencies and delays. This would eventually determine the tools of the Departure Planner, their objectives, where in the system they should be introduced, and how they should be implemented. This paper reports some of the efforts to identify the flow constraints and the dynamics of airport systems based on observations and data analysis [IDRIS et al, 1998]. Some implications for the Departure Planner are discussed in conclusion.

3 FLOW CONSTRAINT IDENTIFICATION

The main purpose of this paper is to identify the flow constraints in the airport system. This is done using both observations at Boston Logan International Airport and data analyses including the ACARS (Aircraft Communication Addressing and Reporting System) delays reports by pilots and the ASQP (Airline Service Quality Performance) data which report landing, parking, pushback and takeoff times automatically through the ACARS system. These analyses and observations will be described for each of the components of the airport system. They include identifying major causes of delays in different components of the system and their interactions, identifying air traffic controllers' strategies to deal with the constraints, and identifying possible control points in the system where the impact of constraints could be reduced effectively.

3.1 The Airport System

Figure 1 depicts the main components of the airport system and the flow of aircraft, arrivals and departures, through these components. Each of the components, the runway system, the taxiways, the ramp, and the gates, constitutes a resource for which the aircraft compete. ATC is also a resource of the system, where the aircraft have to flow through the air traffic controllers in the form of the flight progress strips.

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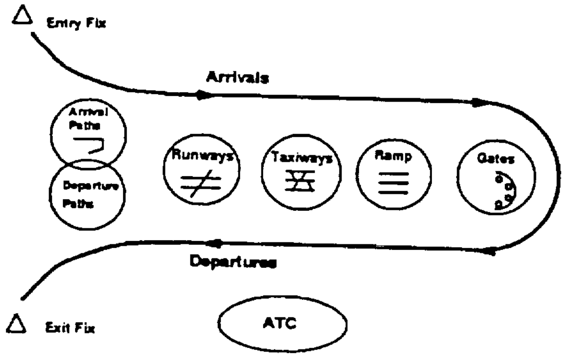

Figure 1: The airport system

Each of these resources becomes a possible constraint to the flow of aircraft, where aircraft, physically and as flight progress strips, have to queue and wait to transition from one part of the system to the next.

3.2 The Runway as a Flow Constraint

The runway system is analyzed as a flow constraint using the ACARS delay reports and causal factors based on observations.

ACARS data analysis

Figure 2 shows the distribution of delay reports by pilots, for one major airline, over major delay cause categories. The pilot delay reports are available through ACARS, which is maintained by most major airlines.. Using the ACARS system pilots voluntarily report the duration and cause of delays suffered under each of the specified categories. The data in Figure 2 include delay reports over a ten-month period for four major airports including Boston Logan. The reports in the Figure are for the delays incurred by departing aircraft between the pushback from the gate (the out time) and the takeoff at the runway (the off time).

The analysis of the ACARS data shows that the runway system is the main source of delay for departing aircraft. Figure 2 shows that for all four airports the delays incurred in the runway takeoff queue, represented in the Figure as the category "other flights landing and departing", account for 55 to 70 percent of the total delays between pushback and takeoff. For DFW these delays amount to over 340,000 minutes. Each of the other categories accounts for less than 10 percent. The similarity in delay causes between the four airports indicates that other airports likely share the same behavior. The ACARS delay reports suffer from a number of limitations: They are subjective human reports, subject to human interpretations of the delay cause categories which may be vague and may overlap; and subject to human errors in estimating the delay times. They are also incomplete since they are voluntary reports by pilots. Despite these limitations, the vast difference between the delays attributed to waiting for other aircraft landing and departing at the runway and the other categories testifies to the fact that the runway system is the main flow constraint to departures in the airport system.

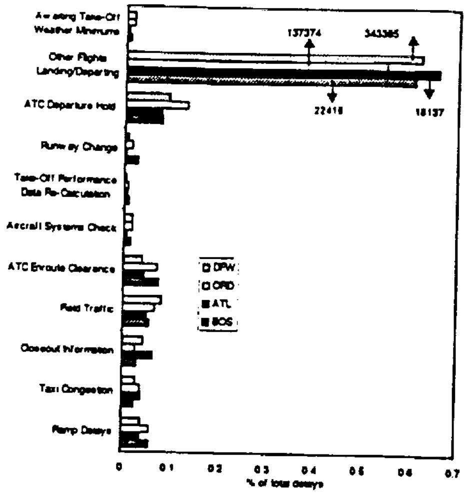

Figure 2:Normalized departure (Out to Off) delays (one airline: Jan-Oct 97)

Causal factors

There are many causes that contribute to making the runway system the major flow constraint, either by limiting the capacity of the runway system or by increasing the demand for it. Some of these reasons, supported by field observations at Boston Logan Tower are listed below:

- **Wake vortex separation requirements:** When aircraft land or takeoff, they occupy the runway not only for the time they are physically on the runway, but also for the duration it takes for the wake vortex they generate on the runway to subside. The time the next aircraft has to wait in the takeoff queue behind another aircraft that just landed or took off depends on the size of the two aircraft. These separations are more complicated and more restrictive when the runway is used for landings as well as takeoffs or when the runway configuration has dependent parallel or crossing runways. For example, a takeoff can start when the next landing on the same runway is at least 2 nautical miles from the runway threshold, or when a landing on an intersecting runway has cleared the runway intersection point. These wake vortex separation requirements limit the capacity of the runway system. The capacity is limited further in bad weather conditions when the required separations cannot be waived and the configuration is limited to a smaller number of runways.

- **Scheduled demand:** The operations at the airport (both arrivals and departures) are usually metered by air traffic control such that the demand for the runway system is on average less than the effective capacity.

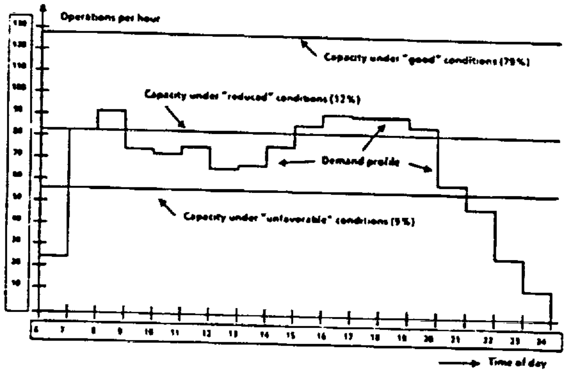

Figure 3: Demand vs. capacity at Logan airport (1987)

Figure 3 shows however that the demand may exceed the capacity at least sometimes during the day. This is due to overscheduling by airlines especially at rush hours or during hub bank operations, lower capacity of the runway system due to unforeseen occurrences such as weather, and the stochastic nature of the arrival process to the runway takeoff queue which is affected by a complex set of upstream processes at the gates, ramp and taxiway systems. It was observed that air traffic controllers try to switch to a high capacity configuration before the rush hours if weather permits. The high capacity configurations are the ones which use 3 runways at the same time, such as 22R for departures and 22L and 27 for arrivals, or the 4R, 4L, 9 configuration mentioned above (Figure 4).

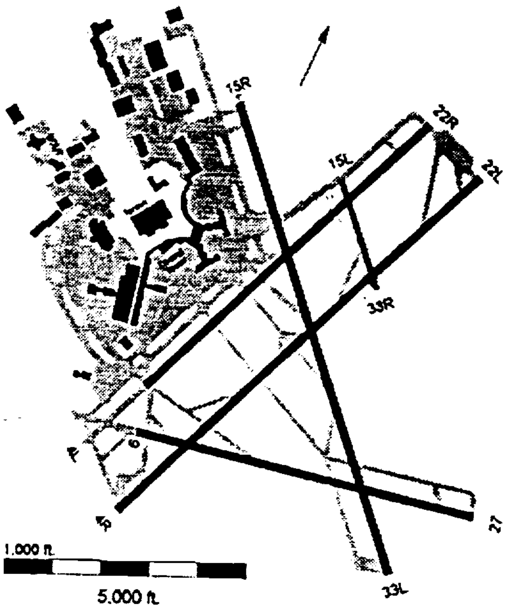

Figure 4: Map of Logan International Airport

- **Capacity limitations due to landing aircraft:** The runway resource providing service to the aircraft in the takeoff queue is sometimes shared by arrivals landing on the same runway or on dependent runways. When the runway is used for both landings and takeoffs, the effective capacity for departures is reduced whenever the capacity for arrivals is increased. This trade-off between arrivals and departures is shown in the capacity envelope in Figure 5 below.

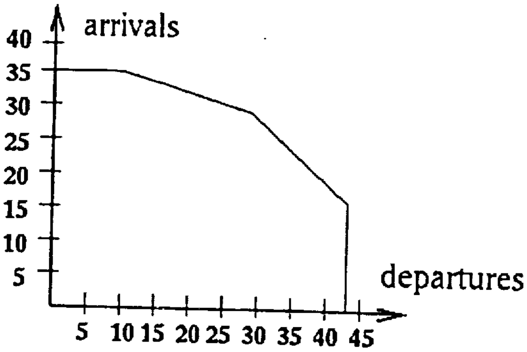

Figure 5: Capacity envelope of the runway system

The curve approximates the Pareto frontier, which corresponds to the maximum capacity of the runway system achievable at the different combinations of arrivals and departures. This frontier can be determined theoretically or experimentally using simulations, given the wake vortex separations mentioned above and the fleet mix at the specific airport. The runway system usually operates at an effective capacity that is less than the maximum given by the capacity envelope, depending on the current conditions [GILBO, 1991].

Air traffic controllers try to match the fluctuations in the arrival/departure mix in the demand, within the allowed tradeoff between arrivals and departures in a given configuration, or through a short-term configuration change. At Boston Logan Tower this is accomplished through coordination between the traffic management coordinator and the TRACON. Two of the tools used to effect changes in the arrival/departure mix when there is a relative departure demand increase, are metering for the arrival runway, and switching a runway from arrivals or mixed operations to departures exclusively, for the duration of the departure push.

- **Runway crossing:** The runway system is also shared by taxiing aircraft that have to cross an active runway. When departures have to cross an active runway used for arrivals, or arrivals have to cross an active runway used for departures, this introduces another coupling between the arrival and departure streams. For example in the 22R-22L-27 configuration described above (Figure 4), arrivals on 27 and 22L have to cross 22R in order to get to the terminal area. These arrivals queue on the taxiways between 22R and 22L, and when the taxiway segments become full the arrivals on 22L and 27 are impeded. The air traffic controllers in this case have to interrupt the departures on 22R in order to let the arrivals cross so that the flow of landings can continue.

- **Downstream constraints:** Restrictions on the flow of departures downstream of the runway may affect the runway operations. For example, it is common that aircraft are handed off to en-route sectors adjacent to the terminal area with in-trail separation requirements in order to control the flow into these sectors. This causes air traffic controllers to favor certain strategies for the departures from the runway in order to ease the process of establishing the in-trail spacing. At Boston Logan, one such strategy is to alternate jet and propeller aircraft departures, because jets usually fly on different initial departure paths than the propeller aircraft do. This increases the separation between successive departures heading towards the same point out of the terminal area.

- **Noise:** A dominant downstream constraint at Boston Logan Airport, are the noise regulations, which restrict operations above certain populated areas. This is an additional factor taken into account by the controllers in adopting strategies for managing departure flows.

- **Delays due to aircraft preparation:** A number of taxi checks are performed by each aircraft before takeoff. These include final weight and balance calculations, systems checks, cabin checks, and deicing in bad weather. An aircraft may be delayed by these processes and hold the rest of the takeoff queue.

- **ATC workload constraints:** Under heavy traffic conditions, the controllers are forced to adopt strategies that ease their workload, while unable to use alternative strategies that may reduce runway waiting time. ATC workload will be discussed in more detail later.

3.3 The Gates as a Flow Constraint

The gates are analyzed as a flow constraint using the ACARS delay reports and causal factors based on observations.

ACARS data analysis

Figure 6 shows the distribution of the delay reports by pilots through the ACARS system for the arrival phase between landing (the wheels on time) and parking at the gate (the in time). These data are for the same airline, period, and airports as the data in Figure 2. The distribution shows that for most airports there is a dominance of the delays due to gate congestion (gate occupied) over the other delay categories, such as ramp and field congestion. Although the dominance is not as prominent as it is in the case of the delays due to the runway system, it is very clear for the Boston and Chicago airports.

Casual factors

Gate capacity: There is a limited number of gates available for each airline, which makes the gates a scarce resource. Observations show that some airlines over schedule their gates at Boston Logan, and use hangar positions to store the aircraft in excess of gates.

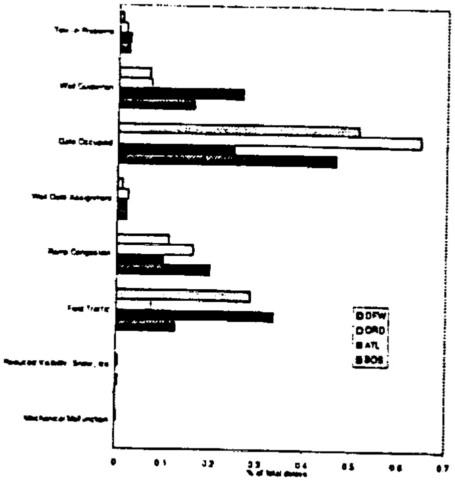

Figure 6: Normalized arrival (On to In) delays (one airline: Jan-Oct 97)

- **Sharing gates between arrivals and departures:** Like the runway system, the gates are another airport resource where arrivals and departures interact. As indicated in the ACARS delay data in Figure 6, large delays are incurred by arriving aircraft when their assigned gate is occupied by a departure. This may occur either because the arrival is early or because the departure is late in pushback.

- **Interdependence between gates:** Aircraft have to wait for each other when they pushback into the same alley. This makes coordinating pushback operations complicated particularly at airports like Boston Logan where the terminal geometry is constrained (Figure 7). At Logan, because the alleys are shared by more than one airline which compete for pushback, the coordination of pushback is done through the tower based on a strict First-Come-First-Serve (FCFS) rule. At most other airports, however, the airlines' stations control the gates and the ramp area.

- **Interdependence between gates and ramp/taxiways:** As shown in Figure 7, some of the gates at Boston Logan pushback directly onto the taxiway system, blocking the taxiway for the duration of pushback and engine startup. Also when an arriving aircraft finds its gate occupied it must wait on the taxiway leading to the gate. This coupling introduces more constraints on the gate operations, and led to the pushback from such gates to be under the control of the tower. This also emphasizes the importance of holding pads where aircraft can wait without holding the traffic stream on the taxiways and ramp. Such holding pads are non-existent at Boston Logan making the gate/taxiways coupling more crucial.

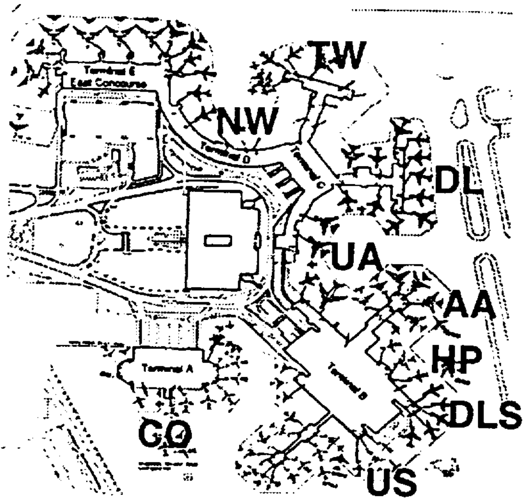

Figure 7: Boston Logan Airport gates

- **Turnaround operations:** While on the gate, aircraft undergo a very complex set of operations to turn it around from an arrival to a departure. Based on observations and interviews with pilots and air traffic controllers, these operations are depicted in Figure 8 in the form of a Petri Net analysis, showing the processes that are required to get the aircraft to the state of 'ready for pushback'. The circles represent conditions or states of the aircraft and other elements of the system, and the bars represent transitions of state, which may be time-consuming processes. Arcs leading from circles to transitions indicate that the conditions represented by the circles must be satisfied before the transition occurs. Once the transition occurs the states represented by circles with arrows coming from the transition are satisfied. Each of the processes in the turnaround contributes to the uncertainties and possible delays that may take place as the aircraft is on the gate. The turnaround operations are managed by the airline's station at the airport. The air traffic controller (the gate controller in the case of Boston Logan) receives a call from the pilot only after all the turnaround operations are completed to indicate that the aircraft is either 'ready for pushback' or 'ready for taxi', depending on the airport, and this becomes his/her only observable state.

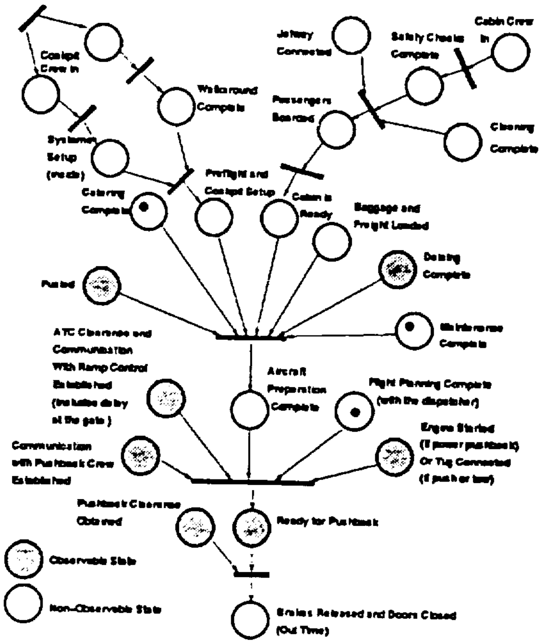
Cockpit Crew In
Walkaround Complete
Systems Setup (inside)
Jetway Connected
Safety Checks Complete
Cabin Crew In
Passengers Boarded
Cleaning Complete
Preflight and Cockpit Setup
Catering Complete
Cabin is Ready
Baggage and Freight Loaded
Deicing Complete
Fueled
Maintenance Complete
ATC Clearance and Communication With Ramp Control Established (includes delay at the gate)
Aircraft Preparation Complete
Flight Planning Complete (with the dispatcher)
Engine Started (if power pushback) Or Tug Connected (if push or tow)
Communication with Pushback Crew Established
Pushback Clearance Obtained
Ready for Pushback
Observable State
Non-Observable State
Brakes Released and Doors Closed (Out Time)

Figure 8: Turnaround Operations

Then the gate, ramp, or ground controller (depending on the airport tower configuration) delivers the pushback clearance to the pilot, the aircraft transitions to the state of 'brakes released and doors closed', and the pushback can commence. However, prior to the call for pushback, the air traffic controller has limited observability on many aircraft states (except possibly for deicing or fueling where the air traffic controller may be able to observe the process from out the window). This prevents him/her from accurately predicting the time of 'ready for pushback', which is the first time that the aircraft is introduced into the ATC system and the departure process is initiated.

Looking at the complexity of the turnaround processes on the gate (Figure 8), it is evident how difficult it is for this controller to predict exactly how many aircraft will call 'ready for pushback' in the next few minutes. Compared with the arrival process, the air traffic controller, or the decision aiding tool e.g. CTAS [ERZBERGER, 1990, 1991] observes the arrival stream proceeding toward the runway and monitors the position and the speed of each aircraft on the radar screen. This makes the flow of arrivals a more observable process where, the air traffic controller can predict the arrival sequence and time quite early and accurately.

Based on the comparison between the different prediction time constants of arrivals and departures, it is hypothesized that the availability of advance departure flow information is essential for better planning of the departure process. The Surface Movement Advisor (SMA) [LAWSON, 1998], which provides some departure delay information to the air traffic controllers, is currently being successfully tested at Atlanta Hartsfield Airport as an information source that assists departure planning. The provision of such information increases the predictability of the departure demand and supports more highly coordinated departure operations.

- **Downstream constraints:** Departures are often held at the gate to meter the flow downstream. This includes the ground hold and miles-in-trail spacing imposed by Flow Control to meter the arrivals into some destination airports that are experiencing capacity limitations. Aircraft are held on the ground to reduce the possibility of more expensive delays in the air. Most of the ground hold is absorbed at the gate before pushback (or in holding pads if available). Departures are also held at the gate by air traffic controllers to meter the flow to the taxiways and the runway system within the same airport. One information feedback mechanism that the air traffic controllers use to estimate downstream congestion levels and the workload level of adjacent controllers is observing the flight progress strips. For example, the gate controller often holds departures at the gate when he/she observes the ground controller overwhelmed by an excessive pile of flight strips.

3.4 The Ramp and Taxiway Systems as Flow Constraints

The ramp and taxiways provide a network of routes which the aircraft, arrivals and departures, use to connect between the runways and the gates. While aircraft interact with each other and with other vehicular traffic at intersections, most of the time spent on the ramp and taxiways is waiting for a runway or for a gate. The ramp and taxiways therefore, provide buffer space for aircraft to queue for takeoff, for runway crossing, and for a gate that is occupied or blocked, as pointed out from earlier observations.

A queuing system

The ramp and taxiway systems can be considered as (or are essentially) a system of queues that leads the departures from the gates to the runways. The capacity of the runway system, given all the constraints mentioned above, determines the service rate for departures and the throughput limits. The taxi out time, which is the time each departure spends between pushback and takeoff, can be considered the time that each departure spends in the queuing system. This time includes both actual taxiing time and time spent waiting in the takeoff queue (and other queues such as at runway crossings). Figure 9 [DELCAIRE, 1998] shows the correlation between the taxi out time and the number of departures, which already pushed back but have not taken off and therefore, are waiting in the queuing system, for Boston Logan.

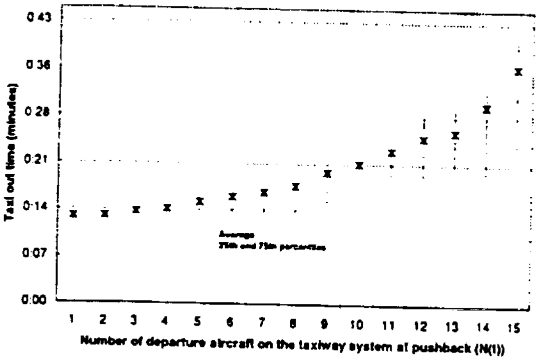

Figure 9: Taxi-out time as a function of the number of departing aircraft on the taxiway system at Boston Logan Airport. (Source: ASQP data for January-March 1997)

The correlation reflects the behavior of a queuing system where the waiting time and the number of departures in the queue are related by the departures' arrival rate. The taxi out time in the Figure is approximated by the difference between the 'wheels off' time and the 'brakes released and doors closed' time, both times are recorded automatically (by activated switches) through the ACARS system. These times are available through the ASQP data, maintained by the FAA, which also include the 'wheels on' time and the parking at gate 'in' time also recorded automatically through the ACARS system. In [SHUMSKY, 1995], it is also indicated that as the taxi out time increases (and therefore, the lengths of the departure queues) the throughput increases up to a limit due to the capacity limitation.

Figure 10 below [DELCAIRE, 1998], shows the high variability of taxi out times for jet operations at Boston Logan Airport. This distribution was constructed using ASQP data from January through March 1997. Results for the Southwest sample (4L-4R-9 configuration) are also highlighted.

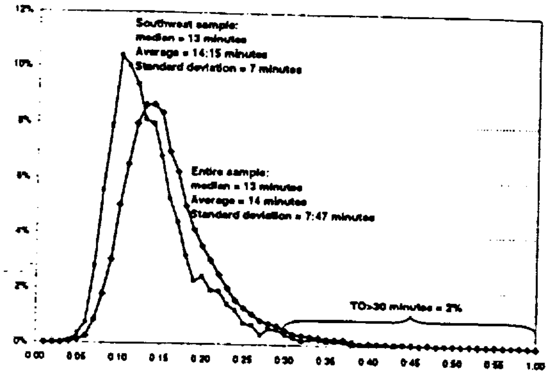

Figure 10: Distribution of Taxi Out Time (in hour:min) for Boston Logan Airport

Queuing dynamics and control point identification

The take-off sequence at the runway is constructed along the path from the gate to the runway. Affected by the dynamics of the airport system, this sequence may be modified anywhere between the gates and the runway. The input to output relationship is analyzed from the ASQP data in order to identify the dynamics of the system between these two points. However, these data are available for the major participating airlines only. Therefore, the analysis conducted here is limited to the dynamics of their operations only, which involve primarily jet aircraft. Despite this limitation, considerable insight into the dynamics of the system is gained. The times of pushback and take-off reported in the ASQP data are sorted and the sequences are generated. The sequence of pushback is compared to the sequence of take-off, and the number of position swaps between the two sequences is determined for each departure. Figures 11 and 12 show the swap magnitude histograms for Boston and Atlanta. Figure 11 shows that for Logan airport, almost 40 percent of the departures did not change their sequence position between the gate and the runway, and on average a jet departure undergoes a one-position swap. Therefore, the dynamics of the departure sequence for Logan appears to be a single FCFS after the aircraft are pushed back from the gates. On the other hand, Figure 12 shows that at Atlanta only about 15 percent of the jet departures do not

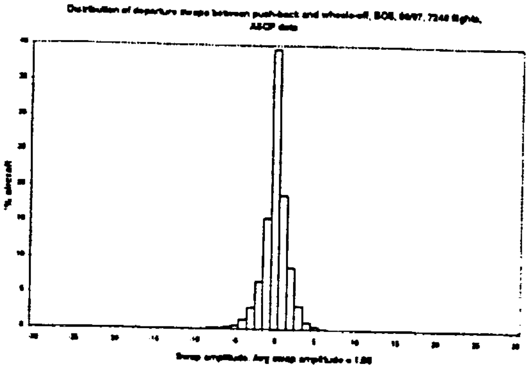

Figure 11: Histogram of the swap magnitude at Logan airport

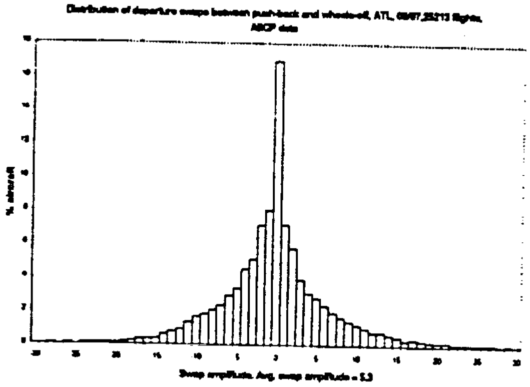

Figure 12: Histogram of the swap magnitude at Atlanta airport

undergo any position swaps in their pushback sequence, while on average, jet departures and the runway. This indicates that at Atlanta experience a swap of 5.3 positions between the gate the dynamics of the departure sequence are not FCFS. An alternative interpretation is that at Atlanta, there is more opportunity to change the departure sequence after pushback from the gate than at Logan airport.

Figure 13 shows the average swap magnitude for 6 airports analyzed. It is clearly demonstrated that the dynamics of the airport system between the gates and the runways, limited to the jet operations, are different for the 6 airports analyzed. Simple models are generated for airport systems based on the insight gained from the analysis above and the airport geometry. Airport systems similar to Boston Logan are modeled with a gate pool and a runway system as shown in Figure 14.

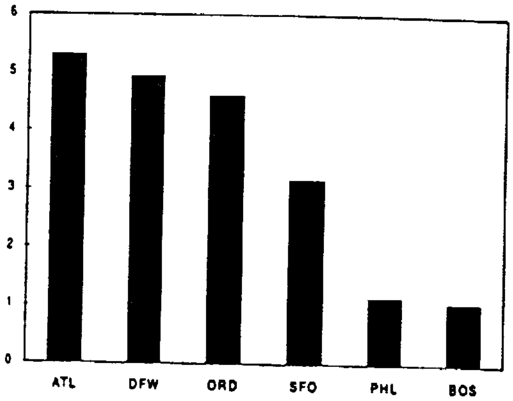

Figure 13: Average swap amplitude at the 6 airports studied

Once departing aircraft push back from the gate pool they join a FCFS queue at the runway. Therefore, a single control point exists at the pushback from the gate, located at the FCFS boundary. The pushback sequence completely determines the take-off sequence, and control action to affect the efficiency of the runway must be taken at the gate.

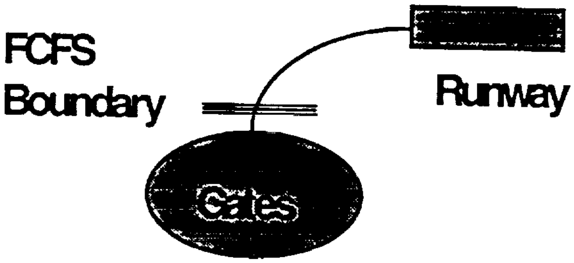

Figure 14: Single runway – single buffer airport system

As shown in Figure 4, the Logan airport terminal area is close to the runway system and once aircraft are pushed back from the gates they are essentially in the takeoff queue. There is no separate ramp area and little space to reorder the aircraft after pushback. In fact there is no ramp control position in the Boston Logan Tower.

The Atlanta airport shown in Figure 15 has two runway systems on opposite sides of the terminal area. Aircraft are pushed back in different directions depending on their runway system and are held at the ramp exits where a sequencing decision is made for each runway system. In Figure 16 a queuing model for such an airport system is shown with a ramp area associated with each runway set. The path to the runway and the pushback sequence are chosen at the gate, while each ramp offers an additional opportunity to affect the sequence at each runway.

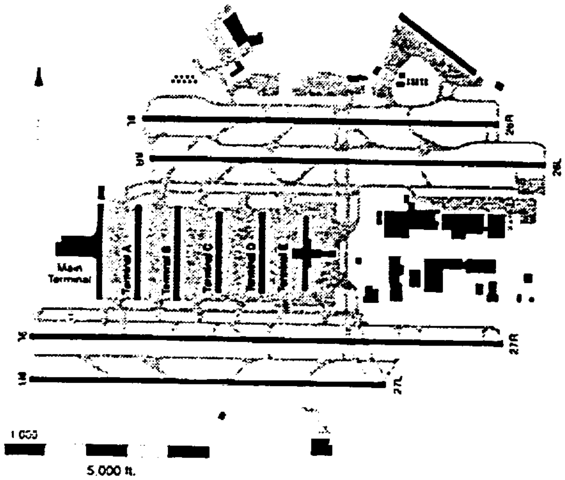

Figure 15: Map of Atlanta Hartsfield international airport

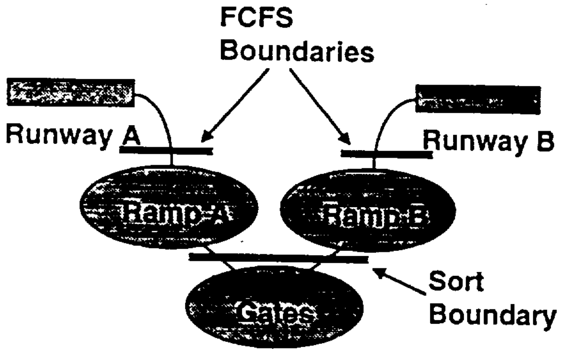

Figure 16: Dual runway – dual buffer – dual path airport system

Comparing ATL and BOS in Figure 13, we may hypothesize that another possible cause for the difference in the swapping behavior between these two airports is the hubbing schedule of ATL, which is not observed in BOS. However, despite the fact that PHL is a hub airport, it exhibits similar swapping behavior to BOS, indicating that the reordering opportunities are more dependent on the geometry of the airport than on the schedule

Note that the models presented above are simplified. More variations and combinations can be developed to model several different airport systems.

3.5 ATC Workload and Human Factors

As aircraft flow through the airport system between the gates and the runways they are constantly under the control of the ATC tower. The number of air traffic controllers in the tower depends on the geometry and the size of the airport. In general however, a gate controller controls the gates, a ramp controller controls the ramp area, a ground controller controls the taxiways, and a local controller controls the runways, as indicated in Figure 17. At Boston Logan for example, there is no ramp controller since most of the gates pushback right onto the taxiway system, and there are one or two local controllers depending on the runway configuration. There are also a flight data position who receives the flight plan and prepares the flight progress strips for each aircraft prior to the gate position, and pre-clearance delivery and gate hold positions which are usually handled by the gate position at Boston Logan.

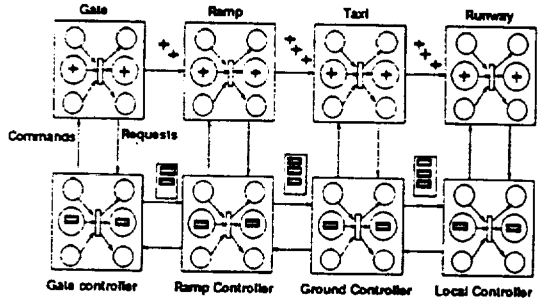

Figure 17: Aircraft/flight strip parallel processes

The air traffic controllers communicate with each other mainly through the flight progress strips. Before an aircraft can move from the control area of one controller to the control area of another controller, the controller hands the aircraft's corresponding flight progress strip to the next controller manually, and asks the pilot to switch to the frequency and communicate with the next controller. There are therefore, two parallel and coupled processes as shown in Figure 17: The flow of the aircraft in the airport coupled with the flow of the corresponding flight progress strips in the tower. As aircraft queue on the surface of the airport, the corresponding flight strips queue on racks in the tower waiting for the controllers attention.

As the congestion level increases the flight progress strips pile up in front of the controllers and the workload level of the controllers increases. This was evident during observations at the Boston Logan Tower, where during the departures peak, the level of communication between the controllers and the pilots increased tremendously. The ground controller for example, would start grouping the commands issued to aircraft, delivering several pushback clearances followed by several handoffs to the local controller, thus attempting to improve the task and communication efficiency. It was also observed that the state of the flight strips piles (or queues) is used as a feedback mechanism to indicate the workload level of the controllers. For example, the gate controller would start holding aircraft at the gate, when observing an excessive buildup of flight strips waiting for pushback clearances before the ground controller. The ground controller sometimes explicitly asks the gate controller to slow delivering departures when overloaded.

Head-down time

Except for the gate controller, controllers observe the state of the aircraft and queues in the airport by continually scanning out of the window and the radar screens. On the other hand, the gate controller is mainly occupied with flight data and other information obtained through a computer station. This has important human factors' implications when developing computer based automation tools such as the departure planner. It implies that the gate position might be most suitable for placing such a tool without significant effects on the controllers' workload. This observation is particularly relevant for Boston Logan, where as indicated by the queuing analysis, the departure processes are best controlled at the gate position before joining the FCFS takeoff queue.

3.6 Environmental Issues

In observing the large buildup of takeoff queues on the taxiways at Boston Logan Airport, issues of environmental impact emerged. One such impact is the high level of ozone emissions attributed to taxiing aircraft with their engines running. Such types of environmental impact are a major consideration in planning departure operations.

4 CONCLUSIONS AND IMPLICATIONS FOR THE DEPARTURE PLANNER TOOL

Based on the observations and analyses presented a number of conclusions and implications for the Departure Planner tool are discussed below:

- **The airport is a complex interactive queuing system:** It is concluded from the observations and the analyses presented in this paper that the airport system is a complex queuing system, where aircraft share the limited resources at the gates, ramp, taxiways and runways as well as the ATC resources in the tower. As the aircraft compete for these resources queues build on the surface of the airport, as well as in the tower in the form of flight strips. These limited resources become potential flow constraints, which impede the flow of aircraft through the system. The system is rendered more complex by the interactions between the different constraints, where a problem in one part of the system, including the tower, can rapidly propagate and cause congestion at other parts of the system.

While departure operations are the main concern of the departure planner tool, it is evident from the observations presented here that there is a large degree of interaction between arrivals and departures on the surface of the airport. Arrivals and departures share many of the same resources in the airport, and arrivals are often given priority over departures due primarily to safety reasons. This is different than the operations in the terminal area where arrivals and departures are separated procedurally using different routes and altitudes. The departure planner tool therefore, does not have the same ability to consider departures separately from arrivals, as does CTAS for example, in concentrating solely on merging the arrivals in the terminal area and the final approach.

- **The runway is the main flow constraint:** Through the flow constraint identification it was determined that there are key constraints to the flow of the departure operations, especially at the runways and gates and in the human factors associated with air traffic control. Of these the runway system emerged as the main flow constraint and cause of delay. This implies that the effort of the departure planning would be most beneficial if targeted at maximizing the performance of the runway system. To do so however, the interactions and the complex nature of the airport system just mentioned should be taken into account in order to determine where and how such an effort should be carried out. To that end the dynamics and control points identification contributes.

- **DP objective function:** In trying to assist air traffic controllers to plan departure operations, the Departure Planner tool must also take into account the varying objectives of all different agents involved in and affected by airport operations (control tower and TRACON, airlines, passengers and surrounding communities). This makes the definition of the objective function for DP a hard problem. Based on the observations and analyses presented, preliminary identification of the main objectives is outlined:

- Maximize the airport operational efficiency and the runway throughput
- Maintain the appropriate balance between arrivals and departures
- Minimize departure delays
- Minimize the environmental impact of emissions and noise by minimizing aircraft taxi-out time
- Maintain fairness
- Reduce controllers' workload
- Provide flexibility to airlines to define and satisfy their own objectives

There are many issues that make the definition of the above objectives difficult, such as the definition of fairness and the definition of delays and assessment of their associated costs. The workload of the air traffic controllers is also an important issue. As observed and demonstrated by other decision-aiding tools such as CTAS, air traffic controllers are not willing to accept an increase in their workload level.

- **Control points and functions:** The swap analysis and control points identification indicate that the structure of the queuing system and the points where the queues are controlled depend on the airport. In the case presented comparing Boston Logan to Atlanta Hartsfield, it is hypothesized based on the swap analysis, that Boston is a one departure queue system, such that aircraft join the FCFS departure queue after the pushback. In such a system departure sequencing should be controlled at the gate. On the other hand, Atlanta has multiple runway systems with at least two departure queues, and a controlled ramp area for each such that there are multiple points where the departure queues can be controlled.

- **Strategic implications:** At a more strategic level a configuration planning function is required to respond to the demand for runway capacity, given the limitations imposed by weather and environmental concerns, such as noise restricted space. Short-term fluctuations in the arrival/departure demand mix are managed through short-term configuration changes as well as relative holding of arrivals and departures. These functions are performed at the level of the Traffic Management coordinator and the supervisor in coordination with the TRACON.

- **Interaction with other automation tools:** It is essential for the development of the departure planner tool to identify its relation with the other automation tools introduced in the terminal area, such as CTAS and SMA. CTAS assists in merging the arrivals to the final approach. It is essential therefore, for providing information to the departure planner about the arrival demand. Given the high level of interaction between arrivals and departures on the airport surface, this information is important for DP, especially for configuration planning and balancing the arrival/departure mix. In addition DP has important inputs to CTAS both in terms of leaving space in the arrival stream to accommodate departure demand, and in terms of transmitting preferences for arrivals based on gate availability. The latter is essential for future applications which would consider gate availability as a factor in ordering the arrivals traffic. The value of SMA was already pointed out in Section 3.3 with respect to forecasting departure demand. The Petri Net analysis of the gate operations showed the volatility and difficulty to predict the short-term departure demand. SMA, by providing information about these operations in the form of departure delays, can assist DP in predicting the departure demand more timely and accurately.

5 ACKNOWLEDGEMENTS

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A CONCEPTUAL DESIGN OF THE DEPARTURE PLANNER

(Working Version 1.1)

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1 Introduction – The Problem

The Departure Planner (DP) concept supports the development of decision-aiding systems, aimed to assist air traffic controllers in improving the performance of departure operations at major congested airports. The design of such systems is expected to increase the overall efficiency of terminal area operations and yield benefits for all stakeholders involved in Air Traffic Management (ATM) operations, users as well as service providers.

Terminal area ATM handles both arriving and departing traffic. To date, research work on terminal area operations has focused primarily on the arrival flow. Automation systems, such as the Center TRACON Automation System (CTAS) and the Terminal Area Productivity (TAP) program, have been designed and implemented in order to manage arrivals, but typically do not take departures into account, except in an approximate manner. Arrivals and departures are highly coupled processes especially in the terminal airspace. Oftentimes, complex interactions and sharing of the same airport resources between arrivals and departures takes place in practically every important terminal area. Therefore, the addition of automation aids, such as DP, for departures, possibly in co-operation with existing arrival flow automation systems, could have a profound contribution in enhancing the overall efficiency of airport operations.

2 The Departure Process – Summary of Previous Results

The development of (possibly automated) decision support tools for air traffic controllers calls for a thorough understanding of links, dependencies and interactions in ATM operations and requires constant evaluation and assessment. For system identification purposes, a first set of field observations was conducted at Boston Logan International Airport [1], [2]. The most important conclusions from this first research stage are summarized here:

1) Data analysis for Logan and other major US airports, such as Chicago O'Hare (ORD), Atlanta Hartsfield (ATL) and Dallas-Fort Worth (DFW) demonstrated significant operational delays and environmental impacts associated with the departure process. It was realized that there is little observability, high volatility and severe data shortages associated with the departure process, as opposed to the more predictable arrival flow. Beyond a certain entry fix point in the terminal airspace, the arrival stream is more or less determined and there is not much opportunity for sequence adjustments. On the other hand, the departure flow is subject to more uncertainty and the controllers have various options in determining the final takeoff sequence.

2) An airport system can possibly be modeled as a complex interactive queuing system in

which departures and arrivals are highly coupled. In [1] and [2] different components of the airport were identified as flow constraints, which introduce delays and inefficiencies contributing to the low prediction capability associated with departures. This is also where departure queues occur in the physical sense. The airport system components that were identified to be the main constraints are

a) The runway system.
b) The gates complex.
c) The taxiway system.
d) The ramp area (where it exists) and

3) Constraint identification was critical in studying the dynamics of departure operations. It enabled the definition of various control points where the departure operations could be affected and it also helped in determining the Departure Planner control options. Each of the control points can be associated with a control function applied to the departure flow. The following control functions were identified:

a) *Pushback* clearance (for jets) or taxi clearance (for smaller aircraft).
b) *Clearance to enter* the taxiway system of the airport from the ramp area, gate or holding pad where the aircraft is waiting.
c) *Runway and taxi-path allocation*, i.e. the process of routing aircraft to a specific runway, through a predetermined taxiway path. Each aircraft usually has an initial runway and taxi-path assignment when leaving its gate. However, controllers frequently implement configuration changes or short-term adjustments to the operations assigned to each active runway in order to accommodate short-term fluctuations in the arrival/departure mix. In such cases, several runway and taxi-path re-allocations may be necessary.
d) *Sequencing* of aircraft destined to take off from the same runway or sequencing of aircraft that are headed for different takeoff queues. As an example we can consider the case when there is a jet aircraft queue and a turboprop aircraft queue and aircraft from both queues are heading to the same departure point. There is a certain amount of sequencing and / or grouping of aircraft from the two queues performed by the controllers, depending on each flight's destination and on downstream constraints in the terminal airspace.
e) *Takeoff release* of each aircraft, which determines the *insertion* of departures into the predetermined arrival flow, in cases when a runway is used for both types of operations. In some cases, departing or arriving aircraft crossing active runways must also be accommodated in the landing and takeoff streams.

Most control functions are applied throughout the departure stream by a sequence of controllers in the tower. For example, aircraft sequencing can be performed at the gate (pushback control), at the taxiway entry points as aircraft are released into the taxiway system and up to the physical point beyond which the aircraft have to commit to a particular takeoff queue. Once the aircraft are physically present at the runway end, the takeoff sequence cannot be modified.

4) Notionally, a control point is defined as the last opportunity that the controllers have to apply a particular control function to the departure queues. A control point can be a physical point on the airport surface, or it can be a point in time during the departure process, when the aircraft transitions from one state to another. For example, a control point exists at the gates when aircraft are cleared to push back into the ramp area. A possible control point is also the instant when aircraft, while taxiing, are handed off to a specific controller who handles a particular set of runways. At that point in time these aircraft are committed to take off from a certain runway, with

no room for further adjustments within their taxiing phase.

The main control points associated with the functions outlined above are:

a) The *gate*.
b) The *point of entry* from the gate or ramp into the airport taxiway system.
c) The *point of commitment* to a specific runway (temporal or spatial) and
d) The *runway* take-off queue.

The exact definition of the control points and the control function pertaining to each of them is *airport specific.* The following example from Boston Logan (BOS) and Atlanta Hartsfield (ATL), supports this argument. BOS is usually operating with one departure queue. The structure of this queue can be primarily determined at the gate (pushback clearance control function), which in most cases is the point of entry into the taxiway system, since the intermediate ramp area in BOS is almost non-existent. On the other hand, ATL has at least two departure queues in most cases, as well as a larger controlled ramp area than BOS does. This means that the structure of the departure queues can be affected at the gate control point, but also to a larger extent at the taxiway entry points and through the mixing of aircraft from different queues.

5) While the main objective of the Departure Planner is to mitigate the existing inefficiencies and reduce the observed delays, an airport system is a multi-objective environment with several stakeholders, such as airport users (airlines, passengers) and ATM service providers. Each of them attaches different "weights" to competing system objectives, which makes it hard to define a single objective function for the DP system. The main system objectives are:

a) comply with safety and separation requirements,
b) maximize system throughput,
c) minimize taxi time (aircraft engine emissions),
d) consider noise regulations and constraints,
e) balance the load on all runways,
f) maintain the controllers' workload at acceptable levels and,
g) provide fair treatment for all airport users

In an effort to satisfy the above objectives, the Departure Planner is designed to include several components, which are examined in detail in the following sections. Each of these components could address a certain aspect of the departure process and its interaction with the arrival flow. The observations and analyses discussed in [2] introduced significant issues that should be accounted for in the design phase of the Departure Planner. The system architecture proposed in the following section describes the control function of each DP component, as well as identifies the point in the system where this function should be introduced. Some implementation issues are also addressed.

3 Overview of the Proposed Departure Planner Architecture

The Departure Planner is intended to assist short term planning operations at major commercial airports. Its emphasis will be on supporting Air Traffic Management in the next 30 to 45 minutes from the current time, but it also has a component that does advance planning with a time-horizon of a few hours. It consists of a set of functional components, some of which could potentially become automation tools used by the controllers to manage the various physical queues existing in the flow of departing aircraft, without increasing workload levels. However, DP is not necessarily viewed as a fully automated system. As presented in Figure 1, it is envisioned to consist of two principal parts: a *Strategic Planner* that would typically have an approximately 3-4 hour time horizon and a *Tactical Planner* with an approximately 30-45 minute time horizon.

The Strategic Planner is essentially a *Configuration Planner* which performs a planning function necessary to respond to the demand for runway capacity, taking into account operational limitations imposed by weather as well as environmental constraints, such as noise restrictions. The primary objective of such a function should be to match the airport's operating capacity to the expected arrival and departure demand by developing an appropriate sequence of configurations that the airport will operate in during a specified planning horizon, which is typically a few hours but may range up to a full day.

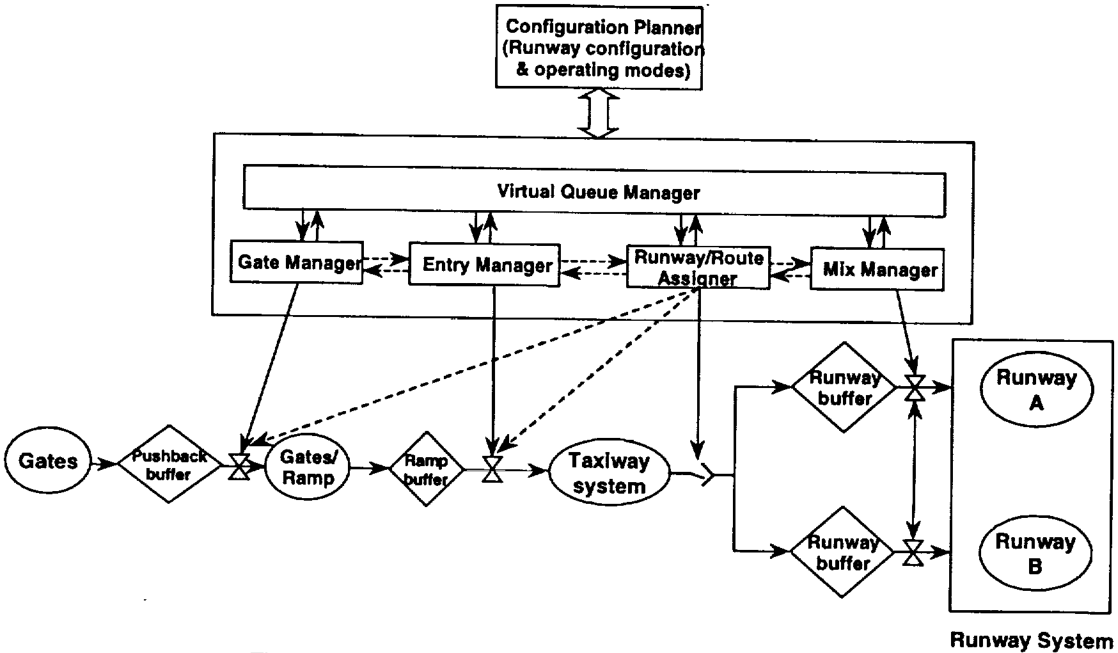

Configuration Planne
(Runway configuratio
& operating modes)
Virtual Queue Manager
Gate Manage
Entry Manager
Runway/Route Assigner
Mix Manager
Gates
Pushback buffer
Gates/ Ramp
Ramp buffer
Taxiway system
Runway buffer
Runway A
Runway buffer
Runway B
Runway System

Figure 1: Overview of the Departure Planner system hierarchy

At a more tactical level, departure operations could be enhanced if a number of existing inefficiencies at specific components of the airport system could be mitigated. Depending on the particular airport where we attempt to enhance ATM operations, there may be a variety of structures of the queuing system and of the control points used to describe this airport's dynamics under different configurations. However, keeping in mind the particularities of different airports and based on the various control options that were identified in Section 2 above, it is proposed here that the tactical core of the Departure Planner system be separated into four distinct components.

In a generic framework that could be applied to any airport, each of these components is designed to exercise control and address inefficiencies at specific control points along the departure process. Each of the components has its localized objectives and its own assigned tasks to perform, while all components communicate and exchange data with each other. Starting from the gates and following the departure flow to the runway takeoff queues, the four system components are:

a) The *Gate Manager*, which is introduced in order to assist controllers in handling the unpredictability, associated with airline gate operations and schedules. Many of the airline operations performed before aircraft are actually ready to push back from their gates are not observable by the controllers. The Gate Manager considers a subset of the aircraft parked at the gates ("pushback buffer" in Figure 1). Based primarily on data on the "readiness" status of each flight and the gate demand from arriving flights, the Gate Manager's main task is to support the controllers in managing the pushback schedule.
b) The *Taxiway Entry Manager* which modulates the release of aircraft for entry into the taxiway system. Aircraft that have pushed back from their gates enter the "ramp buffer" in Figure 1. In cooperation with the Gate Manager, the Entry Manager then determines the sequence and timing of release from the ramp buffer in an effort to minimize the total time that each aircraft spends in the ramp or holding pad areas or taxiing with its engines running.
c) The *Runway/Route Assigner* which suggests runway assignments for departing aircraft and designs and / or implements the takeoff queue size and the takeoff sequence by regulating the release of aircraft to these queues ("runway buffers" in Figure 1). The ability to specify the departure runway that an aircraft will use, provides an additional control point in the departure flow. This control option is exactly what the Runway / Route Assigner tool attempts to exercise.
d) The *Mix Manager* which is introduced in order to manage the arrival/departure mix onto active runways. It regulates the release of departing aircraft from each "runway buffer" onto the corresponding runway (runway A or B in Figure 1), as well as controls the release of aircraft from the runway crossing queues building up on the taxiway segments.

A critical component introduced in the system is the *Virtual Queue Manager*, which takes up the necessary task of coordinating the four tactical DP components. In Figure 1, it is hypothesized to reside in the system hierarchy at one level above the four tactical DP elements. It interacts separately with the strategic configuration planner and with each of the tactical tools. Acting as a central processing function that incorporates all the requests from various physical queues in the system, it relays back to them appropriate control to facilitate a smooth flow of aircraft from one control point to the next. Its main objective is to proactively manage the airport's Virtual Queue so that DP objectives are met. A *virtual queue* can be defined as a notional waiting line of departing aircraft arranged, at any instant of time, according to the order in which they are expected to take off. In other words, the Virtual Queue is the final takeoff sequence of all scheduled departures as the Departure Planner has planned it up to the current point in time. If two or more departure runways are currently in use, or are expected to be shortly, then multiple virtual queues (one for each departure runway) will be in use. As an alternative, in such cases there might be a single virtual queue with each aircraft in the queue being "tagged" to indicate which departure runway it will use.

Next we describe in more detail each of the DP components shown in Fig. 1.

4 Configuration Planner

The main task performed by this strategic element of DP is the development of the configuration plan for the airport so that all arrivals and departures expected to utilize the airport runway resources can be handled. The anticipated terminal weather and the restrictions imposed by the scheduled demand and by environmental regulations (aircraft engine noise and emissions) are the main driving factors in determining the most appropriate sequence of runway configurations that the airport should be operating in.

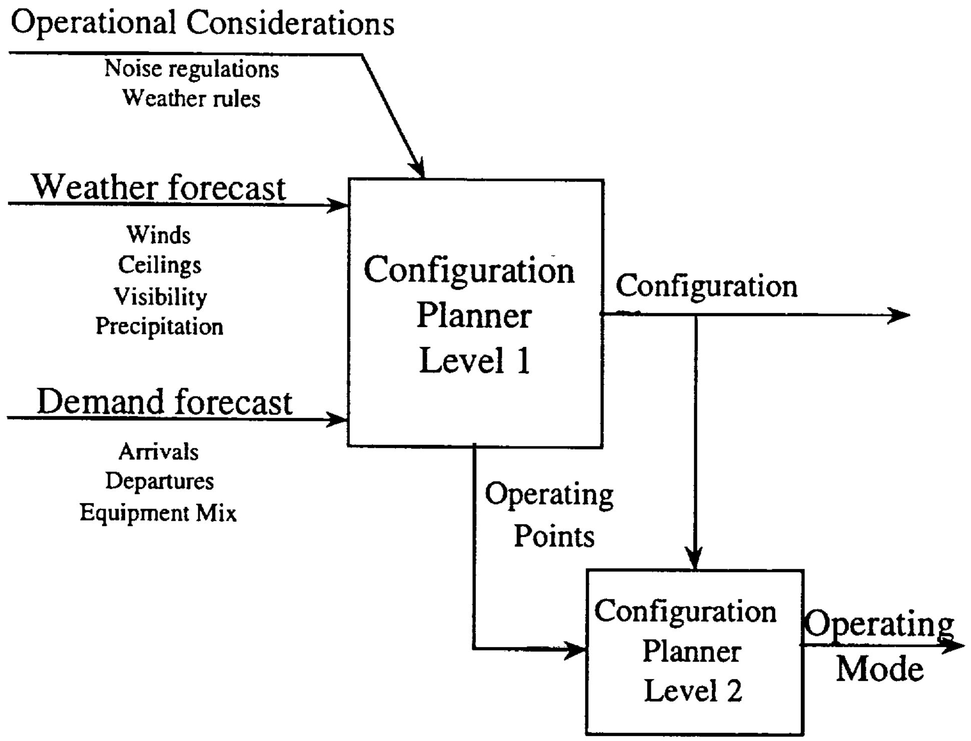

Operational Considerations
Noise regulations
Weather rules
Weather forecast
Winds
Ceilings
Visibility
Precipitation
Demand forecast
Arrivals
Departures
Equipment Mix
Configuration Planner Level 1
Configuration
Operating Points
Configuration Planner Level 2
Operating Mode

Figure 2: The Configuration Planner

As presented in Figure 2, the configuration planner must be designed to take into account the stochasticity (uncertainty) associated with weather (winds, precipitation). Accurate terminal weather and wind forecasts (short term for the next 3 to 4 hours and long term for the whole day) are used to define the set of feasible configurations for the airport. The configuration planner then models the airport capacity for each of these feasible configurations to determine the number of hourly operations that the airport can handle, as well as the associated environmental impact. The expected operations schedule (arrival and departure rates over successive intervals during the planning horizon) is then matched to each of these configurations (level 1 in Figure 2), in order to design the best configuration strategy throughout the day. Matching different possible configurations to the schedule takes into account the time required for transitioning between configurations. This time can take values up to 20 min for a busy period of time at major airports, such as Logan. It depends on the current configuration and on the traffic profile at the time of transition. Usually the TRACON controllers determine the last landing that will be accepted before a configuration change. When the arrival flow is very high, it takes longer to implement a configuration change, because it is harder to interrupt the arrival stream on final approach.

In addition to the transitions from one set of active runways to another, the configuration planner should be able to define discrete operating modes within the time horizon of each of the planned configurations (level 2 in Figure 2). Short-term fluctuations in the arrival/departure mix drive the airport in "departure push" or "arrival pull" mode. In these cases, the air traffic controllers perform short-term configuration changes by adjusting the operations that are assigned to utilize each runway within the current configuration. These configuration changes correspond to transitions between different operating points (Figure 2) on the airport's capacity curve [2]. For example, in normal operations within the 22,27 configuration, runway 22L is used both for arrivals and departures. However, when Logan airport is in a departure push mode, runway 22L is sometimes used only for departures (together with 22R) and all arrivals are assigned to runway 27.

In matching the scheduled demand to the set of possible configurations, one problem that the configuration planning process has to take into account is the uncertainty inherent in departure operations. The departure demand is affected by airline decisions on delays and cancellations, which are not always known sufficiently in advance to provide a solid planning basis for the configuration planner. A step towards addressing this very problem is the information sharing among airlines that has been facilitated through Collaborative Decision-Making (CDM). It has been shown that advance cancellation notices have improved noticeably after the introduction of CDM [4].

5 The Virtual Queue Manager – Virtual vs. Physical Queues

The airport system has been identified as a complex queuing system with physical queues forming at the various flow constraint points that exist along the aircraft departure stream. The *Virtual Queue* in principle can be defined as an extension of the notion of a physical queue. It consists of:

a) A "physical" part, which involves aircraft that are or will shortly be physically present at a certain location on the airport surface, with no further chance for rerouting; therefore, these aircraft have a fixed ("frozen") position in the virtual queue.
b) A "notional" part, which involves aircraft which are scheduled to occupy a particular position in the virtual queue, i.e. have been assigned a position in the sequence of aircraft that will take off. Position assignments in this notional part of the virtual queue are very much subject to revision.

The core of the virtual queue is its physical part and the rest of the queue is basically a projection of how the Virtual Queue Manager plans the queue to be in the future. Depending on which part of the departure flow the core of the virtual queue focuses on, the queue can be designed in a variety of ways. An example design of the virtual queue can be generated if we assume that the core of the virtual queue resides at the runway threshold. In this case, the two parts of the virtual queue may be:

a) The "fixed" part, which includes flights whose position in the queue may be "frozen" a few (10 or 15) minutes before their assigned takeoff time and
b) The "tentative" part, in which the scheduled departure time and the sequencing of some aircraft may be subject to change due to the fact that there is still considerable time to go, e.g., more than 15 minutes until the actual departure event

Figure 3 provides a means to visualize the above example and understand the potential benefits of a virtual queue. Each side of the figure represents a snapshot of the takeoff sequence as it is currently projected in the future. Each line corresponds to a departing flight scheduled to take off within the time span that the virtual queue covers. The left-hand side scenario corresponds to an airport where the departure flow is controlled without implementation of the virtual queue concept, while in the right-hand side scenario, the virtual queue is used for managing departures and determining an optimal (or near-optimal) sequence of takeoffs under pre-specified optimization criteria.

In each case, different aircraft status blocks are identified, each of which corresponds to one of the possible states that a departing aircraft may be in:

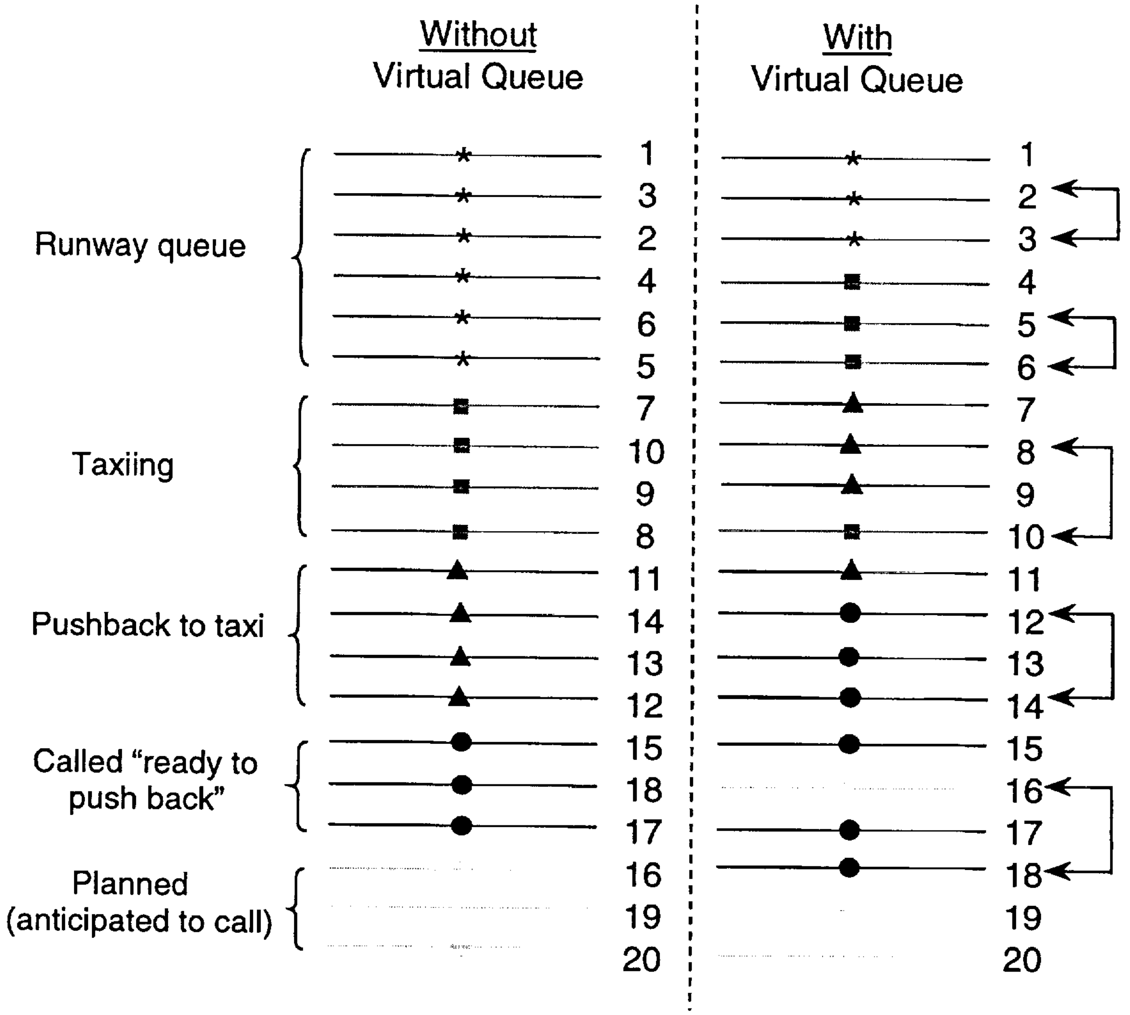
a) At the runway threshold, physically present in the takeoff queue;
b) At a certain taxiing stage;
c) Pushed back from the gate but not yet released into the taxiway system;
d) Waiting for pushback clearance from the tower, after having called "ready for pushback"; and
e) Waiting at the gate and expected to call "ready for pushback" soon.

In both cases the controllers handle the same total number of aircraft. In the "uncontrolled" case, aircraft are pushed back from their gates roughly in the order they call "ready" and they are released into the taxiway system when they reach their taxiway entry point. Naturally, there is a certain level of sequencing performed by the controllers. However, each takeoff queue is fed with aircraft, regardless of how many additional aircraft have already been waiting in the same queue, which often results in overloading the runway queues.

By contrast, the implementation of the Virtual Queue (on the right) provides a tool for effectively controlling the number of aircraft in each status block at each point in time and regulating the timing of aircraft transitions from one status block to the next. Aircraft move from the gate to the ramp onto the taxiway system and into one of the takeoff queues, following the timing and sequence schedule commanded by the Virtual Queue Manager. This schedule is determined based on the system-wide objectives and constraints that were discussed earlier.

Without the presence of a virtual queue, it is very hard in most cases for air traffic controllers to determine mentally the appropriate timing and sequence of departures, while at the same time keeping in mind all constraints and satisfying all system objectives. Therefore, without the Virtual Queue one is more likely to observe unnecessarily overloaded takeoff queues and taxiway congestion. Furthermore, the existence of the virtual queue may assist controllers to determine possible "aircraft takeoff swaps" within the same status block or even between different blocks (arrows on the right side of Figure 3) in order to optimize departure operations. For example, due to wake vortex separation restrictions, an aircraft which has pushed back from its gate but has not entered the taxiway system yet, may assume a position in the virtual takeoff queue ahead of another aircraft that may already be taxiing. An aircraft that has called "ready for pushback" but has not actually left its gate yet, may be scheduled to take off before an aircraft that has already pushed back, possibly due to their different location on the airport relative to the takeoff runway threshold. If there were no virtual queue, these swaps would not be scheduled and some aircraft would take off later than they actually could thus inducing unnecessary departure delays.

In the worst case the virtual queue can be identical to the physical queue, but in general the latter will be a subset of the virtual queue. If carefully defined and managed, the virtual queue may be used to convert taxi delays to gate delays, which are less costly both for the airlines and the environment. In addition, operational flexibility for the airlines can be increased without sacrificing fairness.



Without Virtual Queue
With Virtual Queue
Runway queue
Taxiing
Pushback to taxi
Called "ready to push back"
Planned (anticipated to call)
1
3
2
4
6
5
7
10
9
8
11
14
13
12
15
18
17
16
19
20
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20

Figure 3: Managing the departure sequence of the same 20 scheduled flights, with and without the implementation of a Virtual Queue

The type of queue control exercised and the size of other queues in the airport system determine the size of each physical queue. The major challenge is to design the optimum size of the virtual queue (minimum buffer size) in such a way that none of the queues in the system is ever "starved" (especially the runway takeoff queue) and no queue is ever saturated. It is still a research issue whether the Virtual Queue Manager (VQM) should perform its optimization task interacting with the other DP tools in a pure "Master-Slave" relationship, or whether each of the tools should carry its own processing logic. In the first case, the optimization logic is entirely included in the Virtual Queue Manager and each of the DP components simply relays information and communicates its specific requests to the VQM with the hope that the system status will allow its requests to be satisfied. In the second case, each of the DP tools performs a "first level" optimization dealing with a specific subproblem of the master problem. Subsequently, the Virtual

Queue Manager takes all the requests from the DP elements, which are based on the individual optimization results and attempts a "second level" optimization in order to combine all the "local" solutions into a feasible system-wide solution. This process may involve iterations and re-optimization until such a feasible solution is achieved.

In Figure 3, it is assumed that the virtual queue resides at the runway threshold and the main focus of the Virtual Queue Manager is to manage the departure flow so that the takeoff queues are not starved or overloaded. The "fixed" part of this virtual queue corresponds to the aircraft that are currently (or are committed to be) physically present at the runway end and are controlled by the Mix Manager. The rest of the aircraft included in the "tentative" part of the runway virtual queue are physically present at some other location on the airport surface and are controlled by a different DP element.

6 The Gate Manager

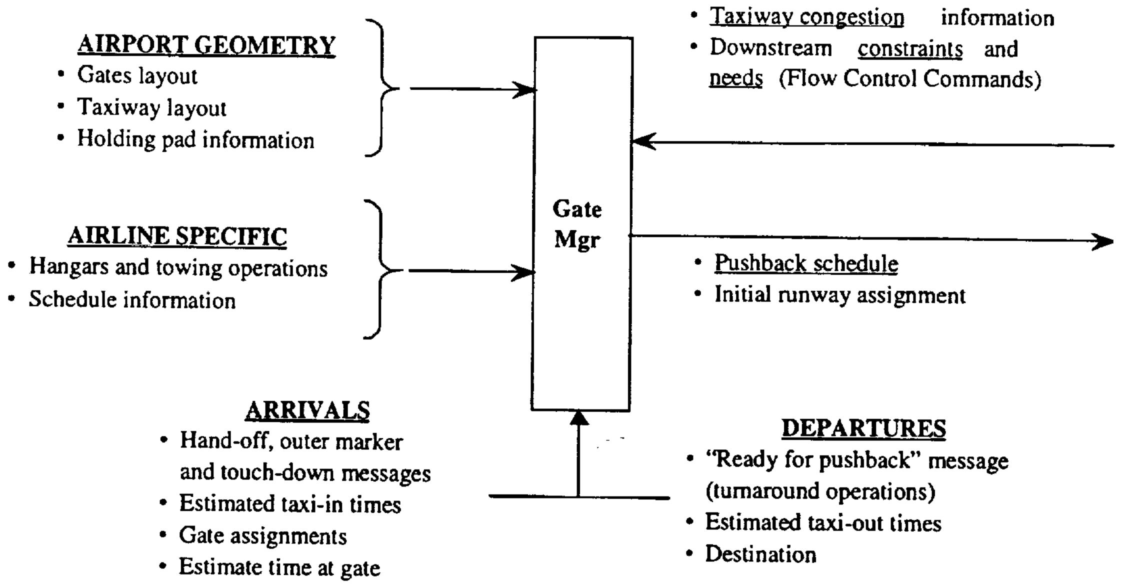
One of the most important conclusions from the field observations at Logan Airport was that the gates often introduce significant constraints in the departure flow [2], [5]. As proposed earlier, the Gate Manager is the DP component that assists the controllers in determining the pushback schedule, subject to the uncertainty associated with airline gate operations. Initial runway assignments for departing flights can also be an important part of the Gate Manager's task.

Example cases, which demonstrate the lack of observability in gate operations and make the controller's task of managing gate pushback clearances more challenging, are:

- Delays and cancellations due to inclement weather, as well as other airline-related factors, such as mechanical problems, result in aircraft being held at their gates and cause unexpected gate blockages. Management of holding pad areas (where available) by the Gate Manager can contribute to resolving such problematic situations.
- Oftentimes, aircraft will call in ready for pushback before their gate operations are actually complete, anticipating the delay between the call for pushback and the actual time that a clearance is granted. To maintain fairness among all airline users, the air traffic controllers usually grant pushback clearances on a First Come (Call Ready for Push Back) First Serve basis. The Gate Manager could assist the controllers in determining a feasible pushback schedule even if they have to deviate from the First Come First Serve strategy.

The Gate Manager is the first DP component that can affect departure operations. Therefore, it has to incorporate and process data generated from the rest of the DP system components. This data exchange is depicted in the form of a "free body diagram", shown in Figure 4. Note that, arrows pointing inwards toward the Gate Manager carry information (flight status data, system constraints) coming from other elements, which are adjacent to the Gate Manager in the system architecture, or from other NAS databases that exchange data with the Departure Planner (e.g. SMA, CTAS). On the other hand, arrows pointing outwards from the DP component convey to the rest of the system commands and requests generated by the Gate Manager function. A similar convention is used to read the "free body diagrams" presented for the remaining system components that are described in the following sections (Figures 5, 6 and 8).

Initially, based on traffic information from the gates, the ramp area, the holding pads and the



AIRPORT GEOMETRY
• Gates layout
• Taxiway layout
• Holding pad information
AIRLINE SPECIFIC
• Hangars and towing operations
• Schedule information
Gate Mgr
• Taxiway congestion information
• Downstream constraints and needs (Flow Control Commands)
• Pushback schedule
• Initial runway assignment
ARRIVALS
• Hand-off, outer marker and touch-down messages
• Estimated taxi-in times
• Gate assignments
• Estimate time at gate
DEPARTURES
• "Ready for pushback" message (turnaround operations)
• Estimated taxi-out times
• Destination

Figure 4: The Gate Manager

taxiway system (Figure 4, top left and right data blocks), the Gate Manager assesses the current airport situation and suggests a feasible pushback schedule within a pre-determined planning horizon. At this stage, relevant data are airline specific ones, such as hangar status and current towing operations, as well as flight specific data and constraints local to each gate, such as destination, "turn-around readiness" messages, and taxi-out time estimates (Figure 4, middle left and bottom data blocks). Such data could possibly be obtained from the SMA database and incorporated in the Gate Manager optimization logic, to provide the system with an accurate estimate of the current and projected airport traffic demand.

In addition to the environmental constraints on emissions and engine running time, important system constraints that must be considered by the Gate Manager are the downstream constraints usually imposed by Air Traffic Control (Figure 4, top right data block). For example, gate holds and Ground Delay Programs involve many cancellations, delays and gate rescheduling and therefore must be communicated to the Gate Manager as soon as all the related information is available from the FAA central flow control (System Command Center).

When there is no ramp area between the gates and the taxiway system (so that the gates can be considered as the taxiway entry point) controlling the gate release times provides an extra opportunity to control the size of takeoff queues and the sequencing of aircraft within the queues. But even if the gates are not taxiway entry points, the additional control option still exists. Based on downstream requests the schedule can be adjusted through gate release control to feed the takeoff buffers with the requested number of aircraft. The system-wide objective of maximizing airport throughput is addressed and pre-allocated departure slots can be met. Engine-running times are also minimized and compliance with environmental emissions regulations is achieved, while gate-blocking delays are significantly reduced. Furthermore, the airlines benefit from fuel savings and late passenger / baggage accommodation by remaining at the gate until they can actually be accepted in the taxiway system, as opposed to pushing back on time and being delayed in holding pad areas or in taxiway queues. This, of course, may have an impact on the on-time departure performance of airlines, as it is currently evaluated. In that sense, the introduction of the Gate Manager's function of managing pushback clearances may call for adjustments in current "on-time performance" evaluation methods.

7 The Taxiway Entry Manager

The interface between the gates and the taxiway system was identified as another possible control point in the departure flow. Depending on the specific airport geometry and complexity, this interface can take various forms. As an example, we consider Boston Logan Airport or any other space-constrained airport. At Logan, there is a set of entry points to the taxiway system, which constitute the interface between the gates and the rest of the airport surface. There is little or no ramp area around the various terminals and in many cases, aircraft push back into active taxiways. On the other hand, other airports, such as Atlanta Hartsfield or Chicago O'Hare, have a ramp area of considerable size, or even holding pad areas adjacent to the terminals. Flights that have to push back when their gate is needed to serve another aircraft, can now be directed to certain corners of the ramp or into the holding pads, awaiting ATC clearance to initiate their taxi paths.

The Taxiway Entry Manager can affect departure operations by regulating the flow of aircraft through the taxiway entry points and the holding pad areas. In addition, it provides another means of controlling indirectly the runway takeoff queues, by controlling the total number of departing aircraft that the next system component (the Runway / Route Assigner) will have to manage and distribute to the various takeoff queues of the airport.

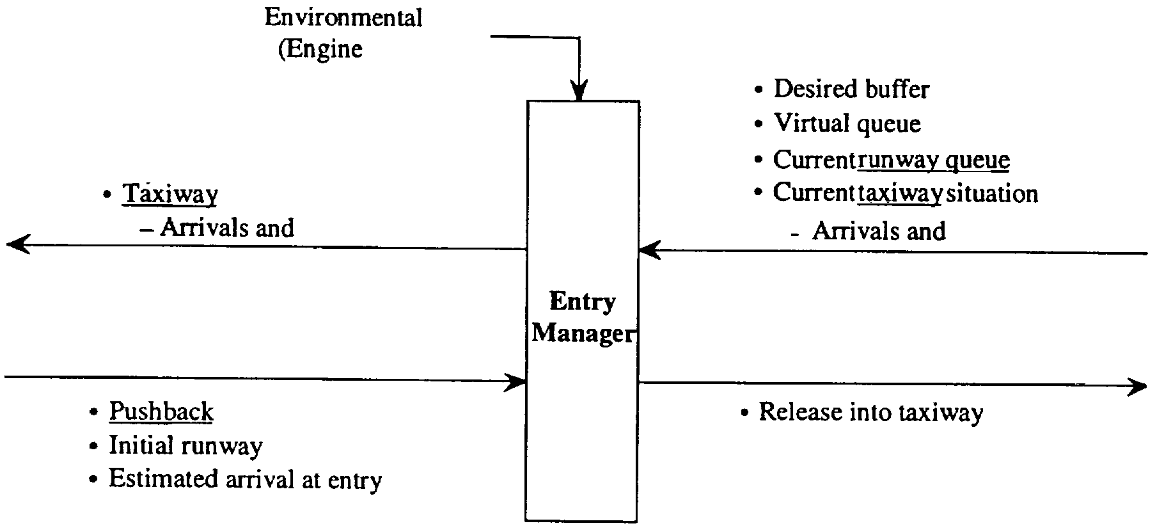


Figure 5: The Taxiway Entry Manager

The current and projected taxiway situation (congestion levels) feeding back from the Runway / Route Assigner and the takeoff queue (buffer) size feeding back from the Mix Manager are the most critical pieces of information for the Taxiway Entry Manager (Figure 5, top right data block). Accurate short-term estimates of pushback operations and prediction of the demand to enter the taxiway system must also be performed and fed into the Entry Manager, in order to avoid overloading the entry points (Figure 5, bottom left data block). All the above information is processed under the constraints of environmental regulations on aircraft engine emissions (Figure 5, top input). The outcome of this system element (Figure 5, bottom right data block) is a feasible schedule of release times for aircraft to enter the taxiway system, which also meets the system objective of minimizing aircraft taxi times and therefore engine-running times, emissions and airline direct operating costs.

As a final note, the control of "aircraft engine-start times" is an additional issue pertaining to the environmental impact from aircraft engine noise and emissions, which deserves further examination. In current operations, only pushback and taxiway entry clearances are commanded by terminal ATC and the exact time that aircraft engines are started is left entirely to the airline's discretion. The Gate Manager and the Entry Manager could possibly schedule the movement of aircraft under the additional objective of postponing engine start times until as close to the taxiway entry clearances as possible.

8 The Runway / Route Assigner

Departing flights usually push back from their gate with an initial runway assignment, which they maintain until takeoff. At space-constrained airports such as Boston Logan, oftentimes aircraft are in the taxiway system as soon as they push back from their gate. Therefore, initial runway assignment decisions have to be made judiciously in order to determine the direction towards which the aircraft will be pushed back and avoid blocking the taxiway and impeding other ongoing operations. Initial runway assignment often determines a default taxi path based on a main flow of traffic on the taxiways, but rerouting on taxiways may occur, especially in cases of taxiway blocking.

In many cases, when particular circumstances necessitate a runway reassignment, the local and ground controllers have a set of decision rules to follow in order to assign the new takeoff runway. When for example, there is a short-term or scheduled runway configuration change or the load in a certain takeoff queue is high, aircraft have to be redirected to a different takeoff runway, a process which may require additional taxi time and induce further delays to many flights.

At most major airports, where more than one departure runway is available in each configuration, there is the potential to adjust runway assignments after aircraft have pushed back or even while an aircraft is still taxiing. In such cases, an aircraft will still leave the gate with an initial runway assignment. A reassignment is feasible only if the aircraft has not reached a "point of no return" in its taxiway path, beyond which it has to commit to the currently assigned runway. The Runway Route / Assigner aims to control this process of adjusting runway and taxi path assignments when necessary, in order to balance the load among all available takeoff runways and achieve a high throughput sequence on each runway.

The Assigner always processes information in cooperation with the Mix Manager, which follows in the system architecture. It considers specific downstream requests regerding the size and sequence of each takeoff queue that come from the Mix Manager, as well as the current status of each of the available runway queues (Figure 6, top right data block). Detailed flight specific information is also important at this stage. The Surface Movement Advisor (SMA) database, which is currently operational only at Atlanta Hartsfield Airport, is a potentially valuable source of such data (Figure 6, bottom left data block). Subject to noise regulations, the Assigner determines which is the most appropriate runway for an aircraft to use from an environmental standpoint (in addition to the load balancing and throughput considerations) and how soon a runway should be reassigned if necessary. Runway assignment decisions are communicated downstream to the Mix Manager to determine the size of and sequencing within each takeoff buffer (Figure 6, bottom right data block) and upstream to provide a complete picture of the takeoff queues to the rest of the system elements for their planning purposes (Figure 6, top left data block).

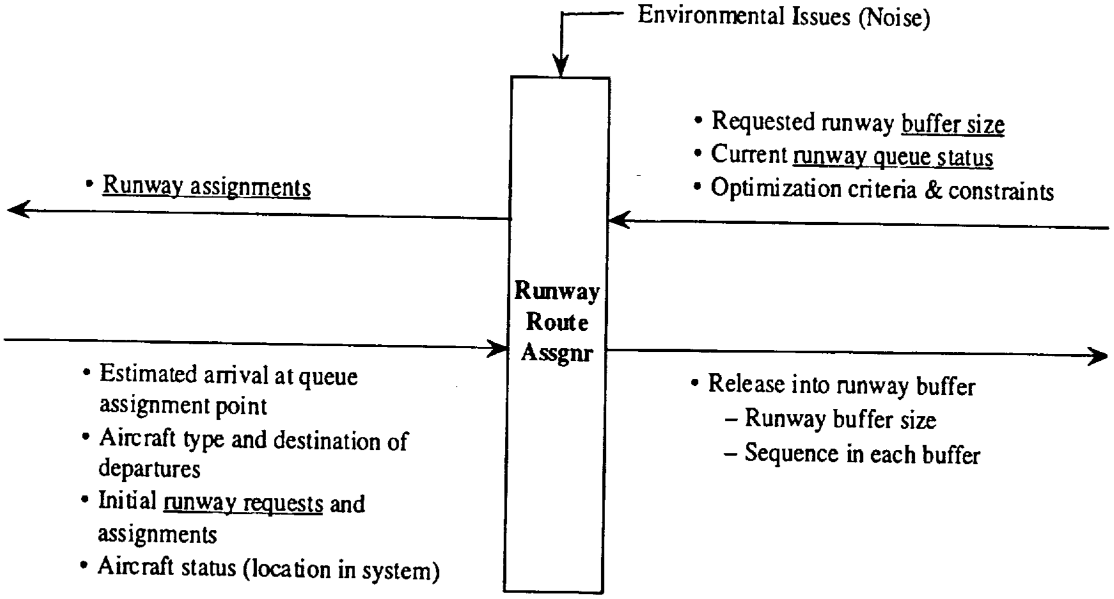

Environmental Issues (Noise)
• Requested runway buffer size
• Current runway queue status
• Optimization criteria & constraints
• Runway assignments
Runway Route Assgnr
• Estimated arrival at queue assignment point
• Aircraft type and destination of departures
• Initial runway requests and assignments
• Aircraft status (location in system)
• Release into runway buffer
– Runway buffer size
– Sequence in each buffer

Figure 6: The Runway / Route Assigner

9 The Mix Manager

Air traffic controllers usually prefer to assign arrivals and departures to different runways. However, this is not always feasible, especially in tightly constrained airports such as Boston Logan. For many configurations, the runway resource utilized by departing aircraft is shared with arriving aircraft, which in most cases have priority over departures. In addition, the runway system is frequently shared with taxiing aircraft that have to cross active runways. Sharing of the runway resources introduces a strong coupling between the arrival and the departure streams. Logan configuration 22R-22L-27 is an illustrative example. In this configuration, arrivals using runways 27 and 22L have to cross runway 22R to reach the terminal area. Crossing aircraft queue in the taxiway segments between runways 22R and 22L but, when there is no more space for queuing aircraft, the departure stream on 22R has to be interrupted for crossings to occur and for making runways 22R and 27 available for further landings.

The coupling between runways (22L and 22R in the above example) suggests that we must consider and manage airport runway resources as sets of dependent runways, as opposed to individual runways. The coordination of operations on dependent runways and the mixing of operations on a single runway are the main tasks performed by the Mix Manager.

As illustrated in Figure 7, the controllers often have to introduce gaps in the arrival stream in an effort to accommodate departures between arrivals and to allow taxiing aircraft to cross active runways. This task entails interaction and coordination with the TRACON final approach, with the objective to maximize the system throughput, while maintaining a fair allocation of delays among the various airport users. This arrival-departure interaction introduces a new complex challenge for existing tools, such as CTAS, which will now have to be enhanced to a different level. The Departure Planner cannot be developed independently from CTAS or other arrival automation tools, which carry information critical to DP for successful configuration planning and arrival/departure mixing. In addition, DP can have important inputs to CTAS and especially Active FAST (Final Approach Spacing Tool), such as the runway crossing and takeoff queue information. These inputs can then be used to determine the most appropriate sequencing and tactical spacing of arrivals (introducing the necessary gaps in the arrival stream, Figure 7).

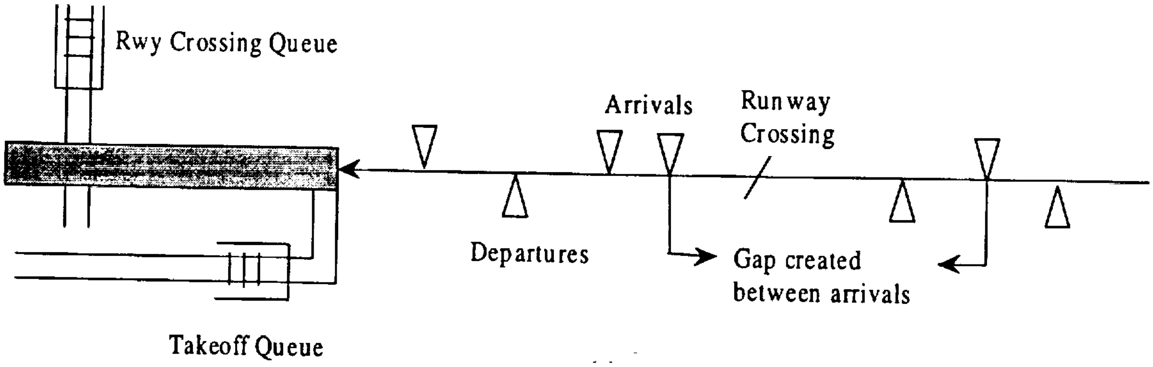

Rwy Crossing Queue
Arrivals
Runway Crossing
Departures
Gap created between arrivals
Takeoff Queue

Figure 7: Arrival / Departure / Runway Crossing Mixing

Figure 8 describes the interaction of the Mix Manager with the rest of the aircraft flow at an airport system. As suggested it is the connective component between terminal airspace traffic

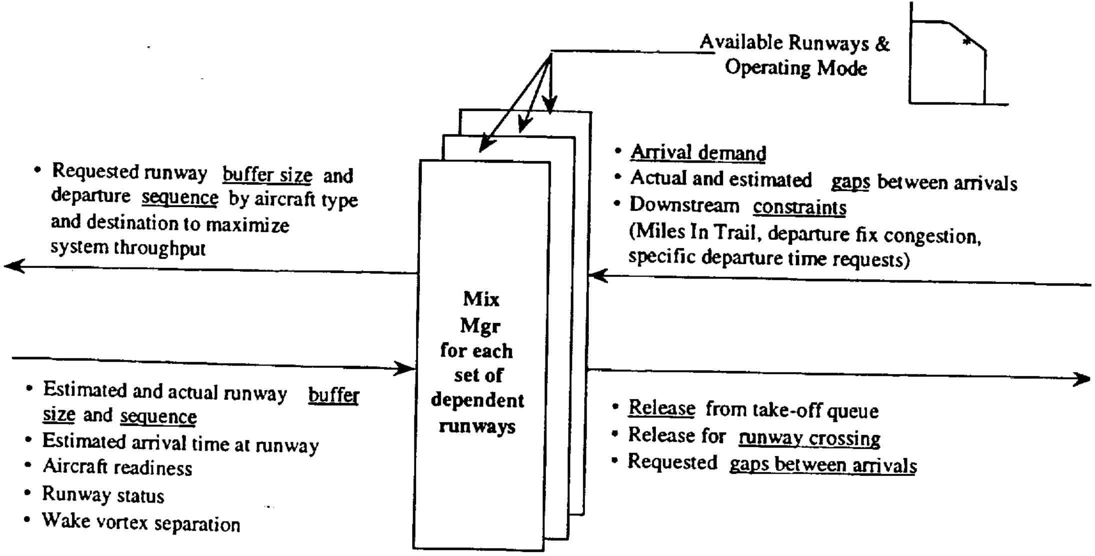

Available Runways & Operating Mode
• Requested runway buffer size and departure sequence by aircraft type and destination to maximize system throughput
• Arrival demand
• Actual and estimated gaps between arrivals
• Downstream constraints (Miles In Trail, departure fix congestion, specific departure time requests)
Mix Mgr for each set of dependent runways
• Estimated and actual runway buffer size and sequence
• Estimated arrival time at runway
• Aircraft readiness
• Runway status
• Wake vortex separation
• Release from take-off queue
• Release for runway crossing
• Requested gaps between arrivals

Figure 8: The Mix Manager

(departures ascending within the terminal airspace and arrival flow approaching the airport) and airport surface traffic (the set of departing or arriving aircraft that are physically present on the taxiway system).

As shown in Figure 8, working under a given runway configuration and a specific mode of operations (Figure 8, top data block), the Mix Manager processes the following inputs:

- Projected takeoff demand information, based on inputs from the actual and projected pushback schedule (Figure 8, bottom left data block).
- Projected landing demand information from the final approach arrival queues that are forming in the terminal area (Figure 8, top right data block).
- Data on downstream constraints, such as miles in trail and departure fix capacity (Figure 8, top right data block).

Collaborative Decision-Making (CDM) can play a vital role at this point, in providing accurately updated demand information (cancellations and delays) to the air traffic controllers and to the mixing function of the Mix Manager.

The main output generated from the Mix Manager is the suggested schedule of aircraft release from the takeoff and runway crossing queues (Figure 8, bottom right data block). Requests for gaps in the arrival flow could be given to the TRACON controllers, in order to implement the suggested takeoff releases. In addition, specific tactical suggestions on the sequence and size of takeoff queues can be communicated to the tower controllers as a basis for carrying out efficiently the gate pushback and taxiway entry processes.

10 Case Study: Boston Logan Airport

Since a prototype system has not been developed yet, evaluating the performance of DP is not possible at this stage. However, the conceptual design of each tool can be demonstrated through an example. We examine a specific runway configuration of Boston Logan Airport in which runways 22L, 22R and 27 are active (Figure 9). First, we illustrate all the different types of aircraft queues that can be formed on the airport surface in this configuration. Then we demonstrate the subset of queues that each of the DP components interacts with, in order to show how these components fit in the system.

As shown in Figure 9, in this configuration runway 27 is usually used only for arrivals, runway 22R is used only for departures and runway 22L is used primarily for arrivals. Often, pilots who specifically request a longer runway for takeoff, use the latter also for departures, in which case they line up and wait on the south taxiway segment between 22L and 22R. When there is a large number of departures expected, the airport switches to "Accelerated Departure Procedures" (ADP), in which case runway 22L is used only for departures and all arrivals are routed to runway 27.

The flow of arriving and departing aircraft through the airport system can be visualized as in Figure 10. The color code is used to distinguish among the various queues forming on the airport surface in this configuration. The physical entities of the airport system (gates, taxiways, runways) are depicted in the middle part of the figure and their interactions with the airport queues are shown as dashed arrow lines. Each line between different queues represents a transition from one queue

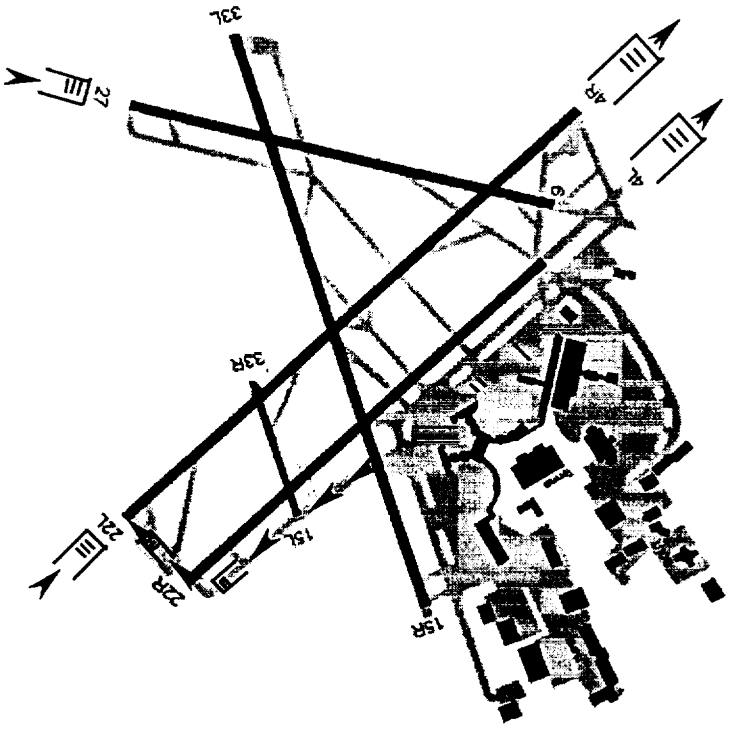

33L
27
4R
4L
9
33R
22L
22R
15L
15R

Figure 9: Logan Airport under configuration 22 / 27

to another. The Virtual Queue Manager acts as the coordinator of all the queues present in the system and manages the timing and sequence of aircraft transitions from one queue to the next.

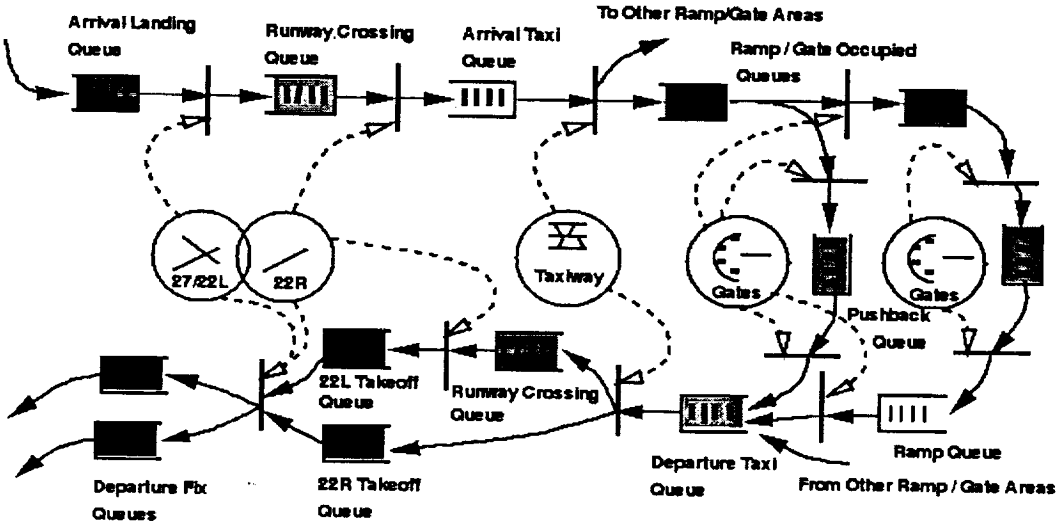

Arrival Landing Queue
Runway Crossing Queue
Arrival Taxi Queue
To Other Ramp/Gate Areas
Ramp / Gate Occupied Queues
27/22L
22R
Taxiway
Gates
Gates
Pushback Queue
22L Takeoff Queue
Runway Crossing Queue
Departure Fix Queues
22R Takeoff Queue
Departure Taxi Queue
Ramp Queue
From Other Ramp / Gate Areas

Figure 10: Queuing Model for Logan Airport under configuration 22 / 27

An arriving aircraft queues on final approach and after landing on 27 or 22L, it joins a runway-crossing queue waiting to cross runway 22R. After crossing, it joins other aircraft in taxiing queues, which may include arriving and/or departing aircraft. Upon arrival at its assigned gate, it may have to wait for the gate to be released from the previous aircraft. When the gate becomes available, the aircraft joins a pushback queue, which includes aircraft expected to depart later in the schedule. In Figure 10, there are two different types of gates presented. In one case (far right side of Figure 10) aircraft that push back from these gates enter the ramp area (e.g. Logan terminal A, point A in Figure 11) and wait in a ramp queue for ATC clearance to enter the departure taxi queue in the taxiway system. In the other case, aircraft push back directly onto the taxiway system with no intermediate ramp area (e.g. part of Logan terminal C, point C in Figure 11). Departing aircraft either enter a runway-crossing queue before joining a takeoff queue, if they are assigned to take off from runway 22L, or enter the 22R takeoff queue directly.

Figure 11 shows the possible location of these queues on the surface of Logan Airport. The two arrival queues on runways 27 and 22L are easily identified, as well as the departure queue that is formed on the taxiway segment adjacent to runway 22R. This departure queue includes aircraft that line up to take off from runway 22R and aircraft that will cross 22R to take off from 22L. Operations on runway 22R are impeded not only by aircraft departing on 22L but also by arriving aircraft that queue in taxiway segments between the two parallel runways to cross runway 22R.

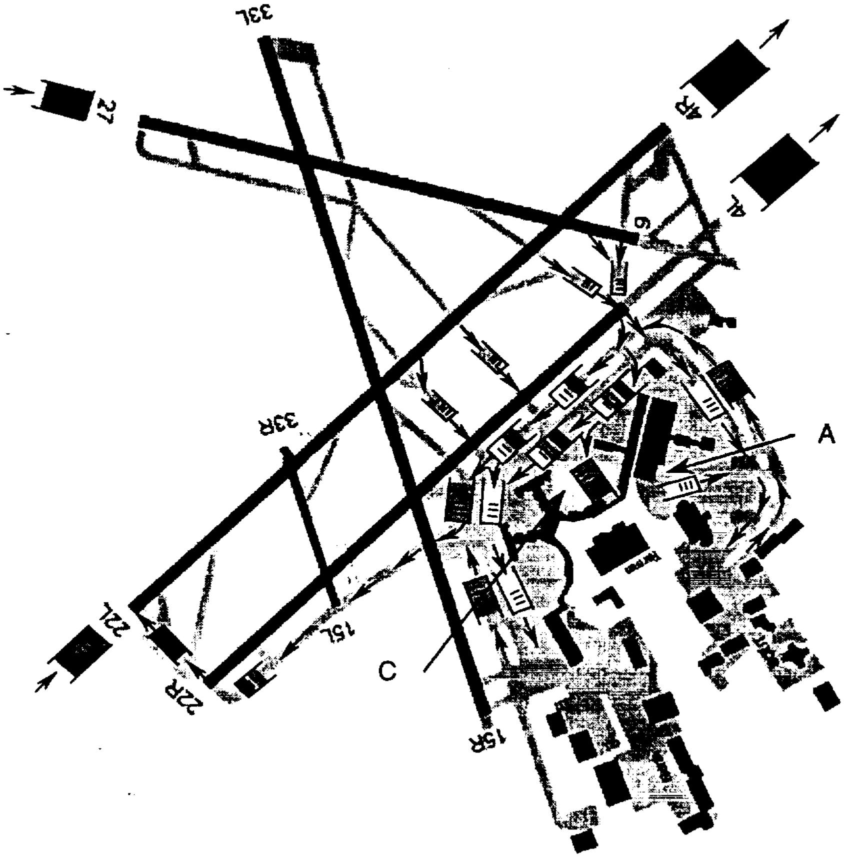


Figure 11: Taxiway and Runway Queues at Logan Airport under configuration 22 / 27

The Mix Manager interacts primarily with the subset of queues shown in Figure 12. It suggests the best time for arrivals to cross 22R given the departure load on that runway. This load is determined based on the number of departing aircraft queuing on the taxiway (information coming from the Runway / Route Assigner) and the number of aircraft assigned to 22L for takeoff. The Mix Manager also manages the merging of the latter aircraft into the arrival stream on 22L. As already mentioned, aircraft that specifically request a longer runway for takeoff are routed to 22L. However, if the airport is running in a "departure push" mode and 22R is not enough to accommodate the departure demand, a few additional aircraft may be sent to 22L for takeoff even if they have not requested it, or the airport may go into ADP. Such decisions must be taken as early as possible so that the Mix Manager has a solid basis to determine the optimum arrival / departure mixing schedule.

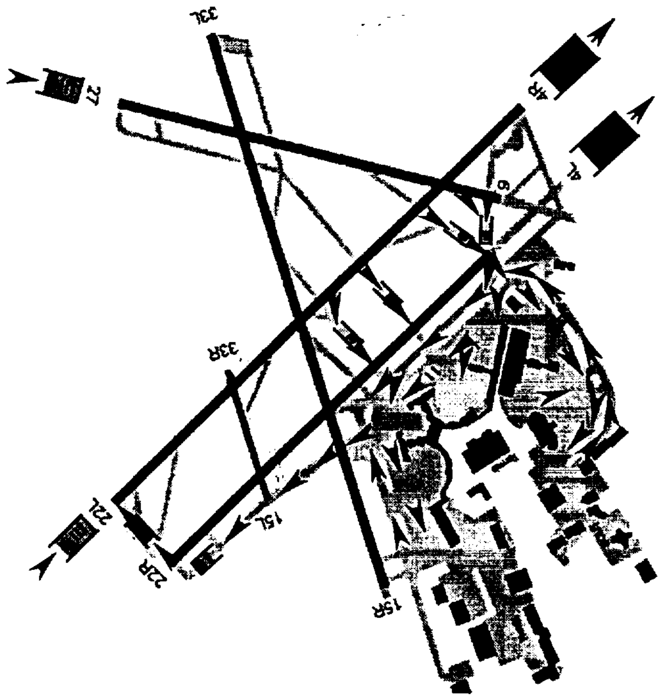


Figure 12: The Mix Manager at Logan Airport (configuration 22 / 27)

The Runway / Route Assigner is the DP component that will process arrival and departure information and decide whether it is necessary to take some load off from runway 22R and assign certain additional departures to 22L. Aircraft queuing on the taxiway segment next to 22R may have left their gates initially assigned to take off from 22R. However, if the current situation dictates a runway reassignment, this can be done even shortly before the 22R runway threshold, which is the "point of no return" or "runway commitment point" for all departing flights in this configuration (point B in Figure 13). However, it is better to have finalized runway assignments as soon as possible in order for the Mix Manager to work efficiently.

Assuming that each DP component has its own built in optimization algorithms, cases like the above will lead to lack of coordination among the different tools. The Mix Manager will request final runway assignments as early as possible. At the same time the Runway / Route Assigner may choose to postpone assignment decisions until it actually needs to make them, in order to account for last-minute changes in the arrival and departure stream that may render its assignments infeasible. The Virtual Queue Manager comes into play in such situations and attempts to determine a common planning horizon for system elements that need to cooperate closely, such as the Mix Manager and the Runway / Route Assigner.

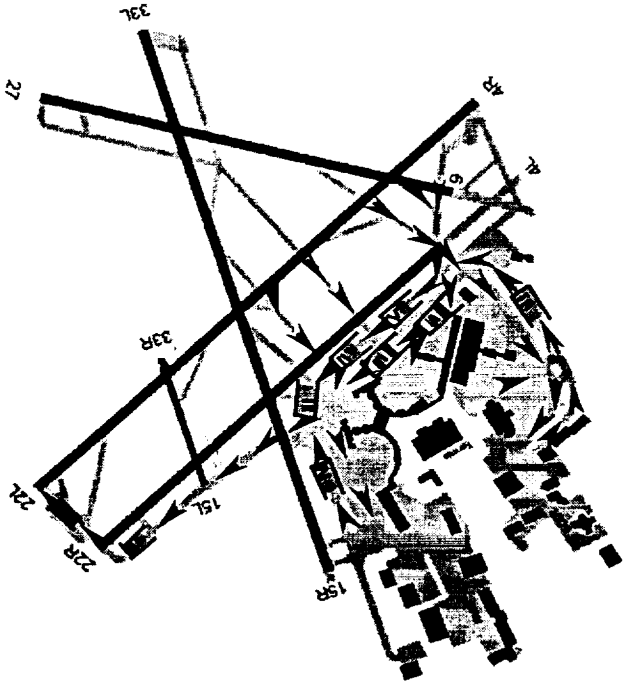

33L
27
4R
4L
9
33R
22L
15L
22R
15R

Figure 13: The Runway/Route Assigner at Logan Airport (configurations 22 / 27)

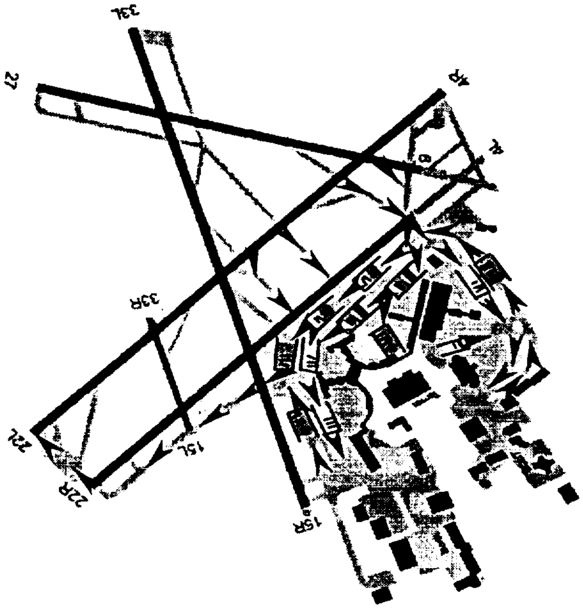

33L
27
4R
4L
9
33R
22L
15L
22R
15R

Figure 14: The Entry Manager and the Gate Manager at Logan Airport (configuration 22 / 27)

The subset of queues depicted in Figure 13 includes the queues that the Runway / Route Assigner primarily interacts with. The multiple color queues include departures that use the same taxiway segments with arrivals (taxiing in or waiting for their gate to be released). The Runway / Route Assigner constantly re-evaluates the situation in all available takeoff buffers and adjusts initial runway assignments to runways as necessary. In the configuration presented here, the only possible adjustment that can be suggested by DP is a takeoff from runway 22L instead of 22R.

The departure, arrival and "gate occupied" queues on the taxiway system are depicted in Figure 14, since these are the queues that are basically controlled by the suggestions of the Gate Manager and the Entry Manager. The Entry Manager evaluates the taxiway congestion level by taking into account not only departing flights, but also arrivals, which in some cases use the same taxiway segments with departures. In addition, aircraft queuing for available gates are considered, since they occupy active taxiway space. It is obvious that the Entry Manager and the Gate Manager operate in close coordination in order to determine the aircraft release schedule from the gates into the ramp or directly into the taxiway system. At Logan airport, ramp space is limited. Therefore, the Gate Manager and Entry Manager functions could potentially be considered as merged into a single tool, which suggests a feasible aircraft release schedule based on downstream constraints (taxiway system congestion, takeoff buffer saturation) and local constraints (gate availability).

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Input-Output Modeling and Control of the Departure Process of Busy Airports

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Abstract

A simple queueing model of busy airport departure operations is proposed. This model is calibrated and validated using available runway configuration and traffic data. The model is then used to evaluate preliminary control schemes aimed at alleviating departure traffic congestion on the airport surface. The potential impact of these control strategies on direct operating costs, environmental costs and overall delay is quantified and discussed.

1 Introduction

The continuing growth of air traffic around the world is resulting in increasing congestion and delays. Average block times between busy city pairs in the U.S. are constantly increasing (for example, the average gate-to-gate time from Boston airport to Washington National airport increased by 20% from 1973 to 1994 [1]). The major bottleneck of the U.S. National Airspace System (NAS) appears to be the airports. In less than ideal weather conditions, arrival and departure capacity can be dramatically reduced, while the airlines are often reluctant or unable to reduce the demand by cancelling flights. The reduced departure capacity can result in very long taxi-out times at peak hours, as the departing aircraft wait in the queue before being allowed to take off. These very long taxi-out times not only increase the direct operating costs for the affected flights, but also result in increased noise and pollutant emissions on the surface of the airports.

It appears therefore desirable to develop mechanisms to reduce these departure queues. The high financial and political cost of increasing airport capacity by adding new runways make a strong case for researching operational improvements to the existing system. This paper develops and validates an input-output model

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of the current departure process at a busy airport, and uses this model to estimate the feasibility and the benefits of departure control mechanisms which aim at reducing departure queues in low capacity conditions.

Many relevant airport models have been developed and described in the literature. Highly detailed (or "microscopic") models such as SIMMOD or TAAM [2], reproduce in great detail the layout of an airport and the operating rules and dynamics of every gate, taxiway and runway for every aircraft type. These models are useful to test procedural changes in routing aircraft on the taxiway system. The downside of these models is the difficulty and high-cost of obtaining statistically significant validation data for all the elements of the airport under many different configurations, and to carry out an exhaustive validation from these data. It is therefore difficult to obtain from these models quick and reliable estimates of the benefits of new operations concepts at the scale of the airport over a long period of time.

Other models, such as the Approximate Network Delays model (A.N.D.) [2] [3], take an aggregate (or "macroscopic") perspective of capacity and demand at an airport over the course of the day and provide estimates of delays. These models allow to study the propagation of delays at the scale of the NAS, but their macroscopic view of the airports does not capture enough details of individual airport operations to study taxi-out time reduction schemes.

This paper takes an intermediate modeling approach, in which input-output models of the airport terminal, taxiway and runway systems are put together to obtain a "mesoscopic" airport model. The airport terminal system and the runway system are modeled as queueing servers, and a stochastic distribution is derived for the travel time on the taxiway system from the terminal to the runway queue. This model captures the departure process in enough detail to estimate the effectiveness of departure control schemes in reducing taxi-out times, while remaining simple enough to allow a rapid validation in each runway configuration. A similar modeling approach was used by Shumsky to develop deterministic models which forecast take-off times of flights from major airports [4] [5]. Some of these models represent the runway system as a queueing server whose capacity is constant over 10 minute intervals. In these models, aircraft reach the runway queue at the end of a nominal travel time on the taxiway system. Shumsky also observed a relationship between airfield congestion and airport departure rate which is the basis of a simple departure control strategy evaluated in this paper. The mesoscopic modeling approach was also followed by Hebert [6], who developed a model of the departure process at LaGuardia airport, based on five days of data, to predict departure delays.

In this model, the departure demand is a non-homogeneous Poisson process, and taxi-out times are modeled as the sum of a nominal travel time to the runway queue and a runway service time. The runway is modeled as a multi-stage Markov process in which service completions follow an Erlang-6 distribution. The runway server can also become absent after a departure, and the absence time distribution is Erlang-9.

The contributions of the present paper are to provide a model of an airport departure process that is thoroughly validated over a year of operational data and to use this model to quantify the effects of departure process control. This work differs from previous publications by the following characteristics:

- the stochastic model of the airport developed in this paper accounts for such explanatory variables as runway configurations and airline terminal location.
- in each configuration, the following model outputs are validated using one year of data:
    - distribution of the number of aircraft on the taxiway system,
    - distributions of taxi-out times in light, moderate and heavy traffic conditions
    - distribution of achieved departure rate
- departure control schemes are proposed and tested on the departure process model. The reduction of runway queueing times achieved by these control schemes is translated into reductions in direct operating costs and pollutant emissions.
- the departure demand used to test the departure control schemes is taken from historical demand records to accurately represent "schedule bunching" (e.g. many flights are scheduled at round times for marketing reasons).

The paper is structured as follows: section 2 introduces the ASQP and PRAS datasets that were used to validate the model and served as a baseline for the testing of new departure process control laws. Section 3 describes in detail the structure on the model and the calibration and validation process. Section 4 introduces simple departure process control schemes and estimates their benefits via computer simulations.

2 Data sources

2.1 Airline Service Quality Performance (ASQP) database

The Airline Service Quality Performance (ASQP) data are collected by the Department of Transportation in order to calculate on-time performance statistics for the 10 main domestic airlines. It includes all the flights flown by the following ten airlines: Alaska, American, America West, Continental, Delta, Northwest, Southwest, TWA, United, and U.S. Airways. For every flight recorded, the database contains the information described in table 1 .

Variable	**Example**	**Comments**
FAA_CARR	AA	Airline
FLTNO	1	Flight Number
DEP_LOCID	JFK	Departure location
ARR_LOCID	LAX	Arrival location
YY	96	Year
MM	12	Month
DD	1	Day
OAG_DEP	847	Scheduled departure time
ASQP_DEP	901	Gate departure time
OAG_ARR	1140	Scheduled arrival time
ASQP_ARR	1152	Gate arrival time
WHEELS_OFF	912	Wheels off time
WHEELS_ON	1139	Wheels on time
TAILNO	N339AA	Tail number
TAXI_OUT	11	WHEELS_OFF - ASQP_DEP (minutes)
TAXI_IN	13	ASQP_ARR - WHEELS_ON (minutes)

Table 1: Data extracted from the ASQP database

This database is made available to the public monthly (with a 2 month delay). The monthly files include around 400,000 flights. For all airlines except Southwest, the "actual" data are automatically reported through the ACARS (Automatic Communications And Reporting System) data link system. For instance, the gate departure time is recorded when the aircraft brakes are released. These data were validated in the case of Boston Logan airport [1] and confirmed that although the brake release signal may differ from the actual start of the push-back procedure, recorded times were very close to the observed ones. Actual take-off times have been made publicly available only since January 1995. Taxi-out time is thus defined in this paper as the time between actual pushback and take-off. At Boston Logan airport, aircraft are constantly under the control of the Airport Control Tower between these two events, while, in the case of some larger hub airports, they are handed off from the airline ramp controllers to the Airport Control Tower at an unknown time. The departure process at an airport such as Boston Logan is thus expected to display less variability. It is also important to mention that since a single company, ARINC, receives these data in real-time, it would be relatively easy to feed them in real time into a control facility.

Note that ASQP data only take into account domestic jet operations, even though regional, turboprop operations can account for as much as 45% of the landing and take-off operations at an airport like Boston Logan. It is assumed in this paper that a useful model of the jet aircraft departure process can still be identified and validated, even though the turboprops do compete for the same taxiways and runways, especially in low-capacity configurations. However, the methods presented here could easily be made more accurate by considering more complete datasets as they become available. In particular, the uncertainties that were observed throughout the study of the departure process could be significantly reduced if more data on turboprop operations were available.

2.2 Preferential Runway Assignment System (PRAS) database

The mix of runways that are in use at an airport any given time is called the "runway configuration". Consider for instance the layout of Boston Logan airport shown on figure 1.

Different departure and arrival runways are used depending on weather conditions and airspace or noise abatement procedures:

- In good weather, parallel visual approaches may be used on runways 4L and 4R to achieve a high landing rate, while departures take place on runway 4R and on the intersecting runway 9 to achieve a high departure rate.
- In bad weather, and if the wings are strong, only one runway (for instance runway 33L) may be available for takeoff and landings. In such configurations, the departure and landing capacity of the airport are greatly decreased.

Figure 1 clearly shows that the travel time of a flight from its gate to the runway threshold will vary significantly with the position of the gate in the terminal and the position of the runway on the airport surface. The runway configuration is therefore an important factor in the airport taxiing operations.

Runway configurations are chosen by the airport tower controllers along the course of the day as the weather evolves. Unfortunately, historical runway configuration data are usually recorded only in logbooks

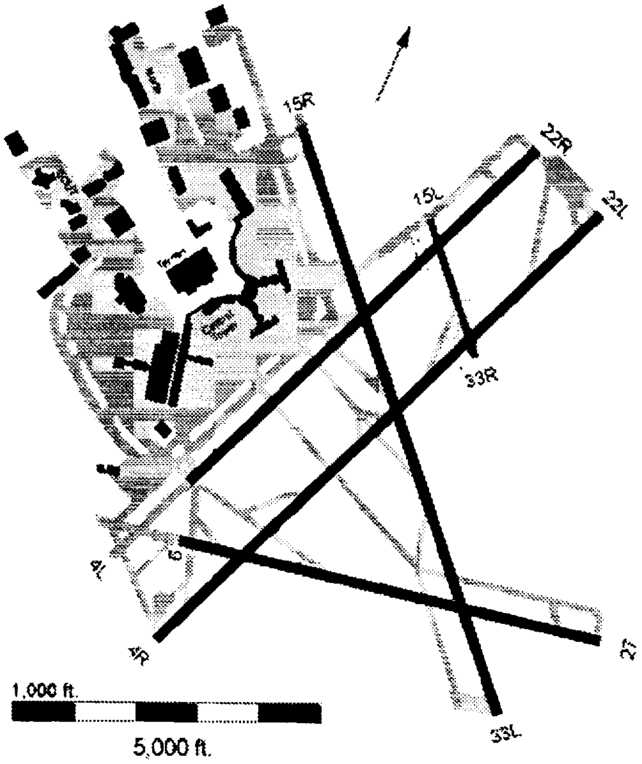
15R
22R
15L
22L
33R
4L
9
4R
27
33L
1,000 ft.
5,000 ft.

Figure 1: Layout of Boston Logan International Airport

and is archived for a limited time. However, to monitor noise abatement procedures, the Massachusetts Port Authority has installed a digital log of runway configurations within the Boston Logan control tower. This paper will therefore concentrate on Boston Logan airport, but the identification and control methods it introduces could be used at any other airports where configuration data would be available.

The configurations in use at Boston Logan airport are shown in table 2, along with the number of pushbacks that took place under each configuration and the approximate departure capacity (in departures/minute) used by the controllers as a benchmark [7]. Note that the airport usually operates in high-capacity configurations (for 81% of the departure operations, the estimated departure capacity of the configuration was above 44 aircraft per hour)

However, the impact of low-capacity configurations is still important since they are associated with departure delays and very long taxi-out times.

No.	**Departure runways**	**Arrival runways**	**% of 1996 pushbacks**	**Departure capacity** (aircraft / hr)
1	33L	33L-33R	1.5	26
2	27-33L	33L-33R	15.7	44
3	4R-4L	4R-4L	2.9	50
4	22R-22L	22L-22R	5.3	34 to 44
5	15R-22L	22L-22R	1.6	34
6	15R	15R-15L	0.3	26
7	22R-22L	27 - 22L	31.3	50
8	9-4R-4L	4R-4L	24.4	50
9	9-4R	4R	3.9	34
10	9-4R-4L	4R-4L-15R	8.0	34 to 50
11	15R	4R-4L	1.4	34
12	4R	33L-33R	0.1	N/A
13	33L	15R	0.4	10
14	22R-22L	33L-33R	0.2	N/A
15	33L-33R	27	0.1	50
16	27-33L	27	0.2	50
17	4R	4R	0.5	34
18	9-15R	15R-9-15L	0.6	44
19	22L-22R	27 ADP	0.6	44 to 50
20	15R-9	15R	0.9	N/A
22	27-33L	33L-27	0.2	N/A
25	9-33L	33L-33R	0.02	N/A

Table 2: Configurations at Boston Logan International Airport

3 Model Calibration and Validation

Subsection 3.1 outlines the structure of the model. Subsection 3.2 explains in detail the calibration process of each element of the model. Subsection 3.3 presents validation results on the whole model.

3.1 Model Structure

A schematic of the model is shown on figure 2. The evolution of the system is modeled over discrete 1-minute time periods: $t = 1, 2, ...$

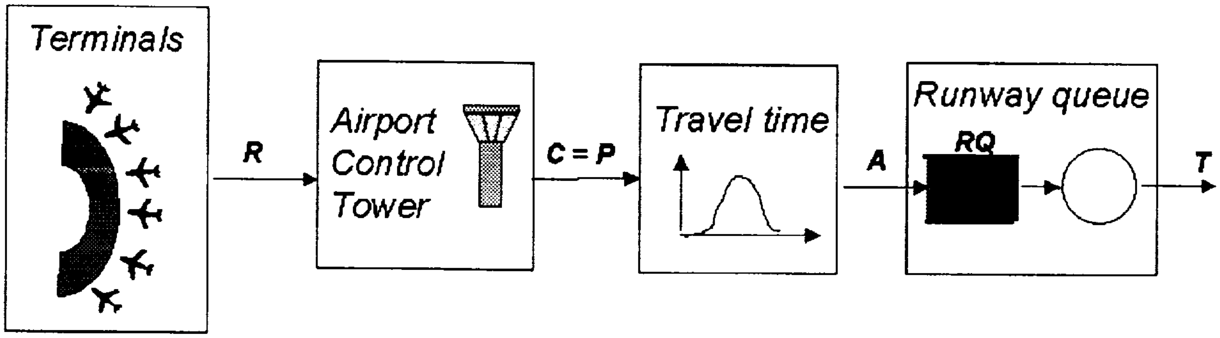

Figure 2: Structure of the departure process model for current operations

Define:

$R(t)$ = the number of pushback requests during period t.
$C(t)$ = the number of aircraft which are cleared to push back by the airport tower controllers during time period t
$P(t)$ = the number of pushbacks actually taking place during period t.
$N(t)$ = the number of departing aircraft on the taxiway system at the beginning of period t.
$A(t)$ = the number of aircraft reaching the runway queue during period t.
$RQ(t)$ = the number of aircraft left waiting in the departure queue on the taxiways at the end of period t (note that this queue may in some cases be spread between several departure runways)
$RC(t)$ = the capacity of the departure runways during period t.
$T(t)$ = the number of take-off during period t.

The dynamics of the model are as follows:

- Airport Tower control action:

  $C(t)$ is determined by the airport tower controllers, and can take into account:

  - the current traffic conditions on the airport surface
  - the current requests $R(t)$

  - the forecasts of future departure demand and capacity

  It is assumed here that aircraft push back immediately after receiving their clearance, so that $P(t) = C(t)$.

- Travel time:

  The arrivals at the runway queue $A(t)$ are related to pushbacks $P(t)$ through travel times in the following way:

$$A(t) = \sum_{\tau \geq 0} [\sum_{k=1}^{P(t-\tau)} U(t-\tau, k, \tau)] \tag{1}$$

  where $U(t-\tau, k, \tau)$ is an indicator random variable which takes the value 1 if the k-th airplane pushing back at time $t-\tau$ has travel time τ to the runway queue.

- Runway queue:

  The runway queue satisfies the following balance equation:

$$RQ(t) = RQ(t-1) + A(t) - T(t) \tag{2}$$

- Take-off:

  The achieved take-off rate depends is limited the runway capacity $RC(t)$ and by the number $RQ(t)$ of aircraft available for take-off:

$$T(t) = \min([RQ(t-1) + A(t)], RC(t)) \tag{3}$$

In addition, the "taxiway loading" parameter $N(t)$ satisfies the following balance equation:

$$N(t) = N(t-1) + P(t-1) - T(t-1) \tag{4}$$

3.2 Model Calibration

The purpose of the calibration is to observe historical inputs and outputs of the systems and to deduce "best" values for the model parameters.

3.2.1 Pushback requests and clearances

Figure 2 shows that the input of the model is the number of pushback requests $R(t)$. However this input is not captured in the ASQP data. Indeed, the OAG (Official Airline Guide) only reflects the scheduled departure times but does not account for internal airline events or decisions which could delay the request for pushback of a flight. In addition, the control action of the airport tower controllers between the requests for pushback and the actual pushbacks are not observed. Consequently, the model identification presented in this paper focuses on the motion phase of the departure process, i.e. the part of the model between $P(t)$ and $T(t)$. Hence, the input used for model calibration is now the number of pushbacks $P(t)$ during period t, which is the number of actual departures recorded during period t in the ASQP data.

3.2.2 Taxi-out times

The travel time from the terminals to the runway is not directly observed in the ASQP data. Indeed the taxi-out times listed in the ASQP dataset are measured from pushback to take-off, and are therefore the sum of the travel time to the runway queue and the runway queueing time.

Observations of ASQP taxi-out times at off-peak hours, when $N(t)$ is very low, give a good indication of travel time, since this will usually correspond to periods with little or no runway queue.

For an aircraft k, define $N_{PB}(k)$ to be the value of N when aircraft k pushes back (i.e. the number of departing aircraft on the taxiway system when aircraft k pushes back). Figure 3 shows a typical distribution of the ASQP taxi-out times for aircraft such that $N_{PB} \leq 2$. Note that this travel time includes the take-off roll and initial climb until the time when the ACARS take-off message is sent.

The variability in these distributions arises from several factors:

- variability in the duration of the actual pushback and the engine start
- different flights from the same airline can be assigned different departure runways or different taxi routes to the same runway
- taxi speed can be affected by visibility and aircraft types
- aircraft bound to certain destinations receive their weight and balance numbers later than others and thus take longer to enter the runway queue

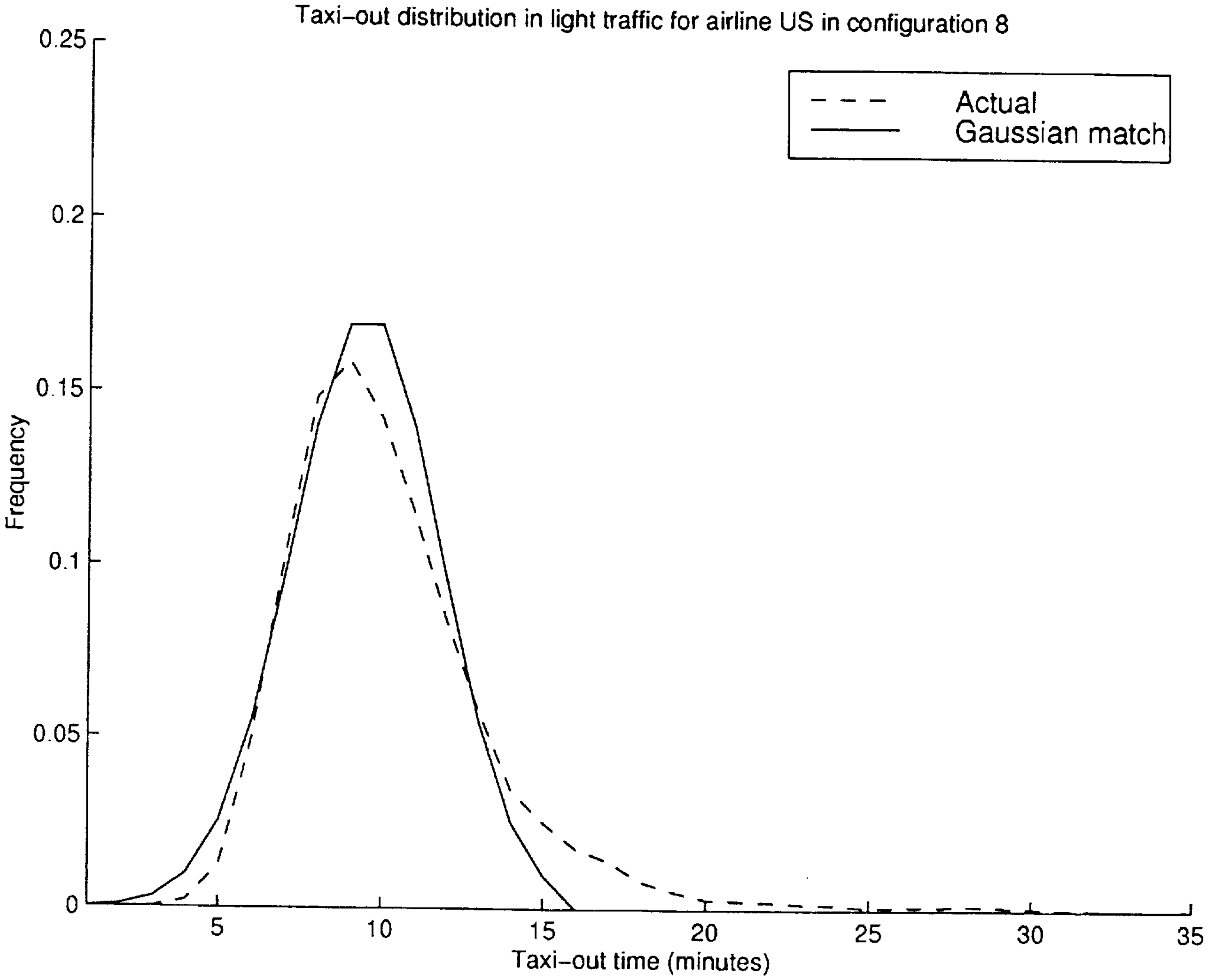

Figure 3: Selection of a Gaussian distribution to match a light traffic taxi-out distribution

In this paper, these factors are modeled as stochastic uncertainty. Gaussian distributions are fitted to the observed distributions to obtained a reasonable model of travel time for low values of N. For instance, a Gaussian distribution with mean 9 minutes and standard deviation 2.3 minutes was selected for the airline shown on figure 3.

A simple estimate of the taxi-out time is then:

$$\tau = \tau_{travel} + \tau_{queue} \tag{5}$$

where:

τ_{travel} = travel time following the light traffic distributions described above.

τ_{queue} = queueing time at the runway.

Note that this model will slightly overestimate the taxi-out of time when N is large, because it does not take into account the fact that as the runway queue grows, the travel time τ_{travel} to reach it decreases.

3.2.3 Departure process

The dynamics of runway systems have been the object of numerous studies and publications [8] [9]. However, discrete event departure runway models which consider each take-off individually remain difficult to identify and validate. Indeed, while there is some data available on the output of the runway system (e.g. ASQP take-off times), little or no objective and statistically significant data is available on its inputs:

- times at which aircraft join a departure runway queue
- runway crossings by taxiing or landing aircraft
- landings on departure runways
- landings on intersecting runways
- take-off of turboprop aircraft

Thus an analysis of inter-departure times cannot precisely distinguish whether a longer than average service time is due to a momentarily empty runway queue or to a server absence (such as a landing or runway crossing).

The analysis of ASQP take-off data is further complicated by the poor time resolution of the dataset (the one minute time increments are comparable to typical runway service times).

The approach that is taken in this study is to identify periods of time when the runway queue was unlikely to be empty, and to consider that the histogram of take-off rates over these periods of time is a good approximation of the theoretical runway service rate distribution. This approach would be easy to implement if the runways queue length $RQ(t)$ could be directly observed. But since no runway queue length data is currently available, the number $N(t)$ of departing aircraft on the taxiway system is used instead. It will be shown that $N(t)$ is indeed a good predictor of the runway loading over some period of time after t.

Define $\bar{T}_n(t)$ to be the "moving average" of take-off rate, i.e. the average of take-off rate over the time periods $(t-n, ..., t, ..., t+n)$. A normalized correlation plot of $N(t)$ and $\bar{T}_5(t)$ under configuration 8 is shown on figure 4 (i.e. figure 4 shows $\frac{||N(t)\cdot\bar{T}_5(t+dt)||}{||N(t)||\cdot||\bar{T}_5(t+dt)||}$ as a function of dt)

The maximum correlation occurs for $dt = 6$, i.e. between $N(t)$ and $\bar{T}_5(t+6)$. This means that $N(t)$ predicts best the number off take-off over the time periods $(t+1, t+2, ..., t+11)$. (Note that this is consistent with the travel times, which are typically around 8 to 15 minutes at Boston Logan airport). Figure 5 presents histograms of $\bar{T}_5(t+6)$ for different values of $N(t)$ for configuration 8 in 1996 (departures on runways 9-4L-4R and landings on runways 4R-4L). This is a high capacity, good-weather configuration that is used often throughout the year at Boston Logan. As shown in table 2, it accounted for 24.4% of all pushbacks in 1996.

As N increases, the take-off rate increases at first, and then saturates for $N \approx 9$. This phenomenon had been described in an aggregate manner (i.e. considering all the runway configurations together) by Shumsky [4] [5].

The runway system model used in this paper is shown on figure 6. It is based on the server absence concept. For each time period, there is a probability p that the runway system is not available for take-off. If the runway system is available however, its capacity is c aircraft over one time period (i.e. one minute). Subsection 3.3 will demonstrate that even such a simple model of a complex multi-runway system can reproduce very precisely the dynamics of the departure process . Note that in this model during each time period the runway capacity is the result of a Bernouilli trial[10] (with success if the runway system is available for take-off), so that the departure capacity $\bar{T}_n(t)$ over the $(2n+1)$ time periods $(t-n, ..., t, ..., t+n)$ follows the binomial distribution:

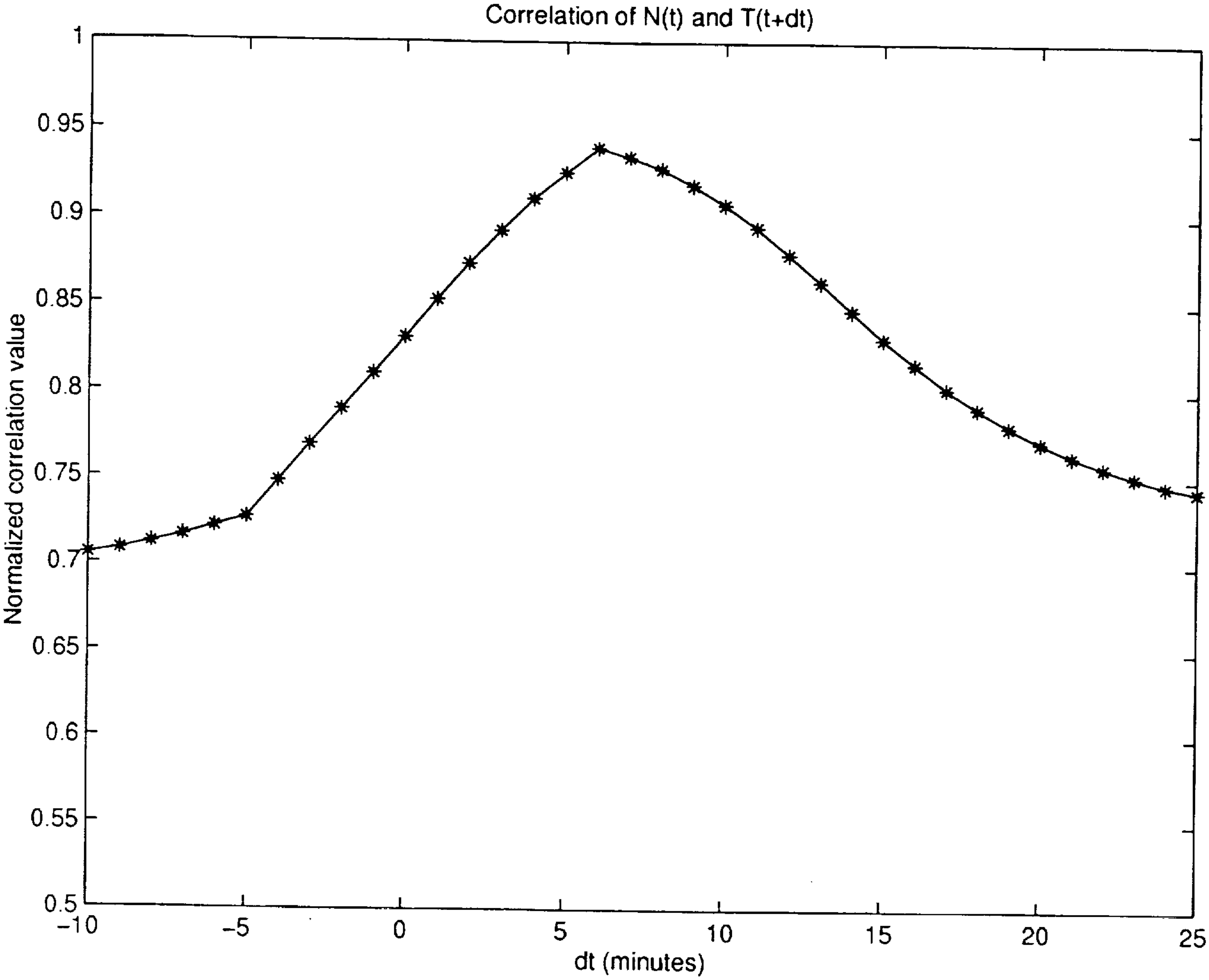

Figure 4: Configuration 8: $N(t)$ is well correlated with $\bar{T}_5(t+6)$

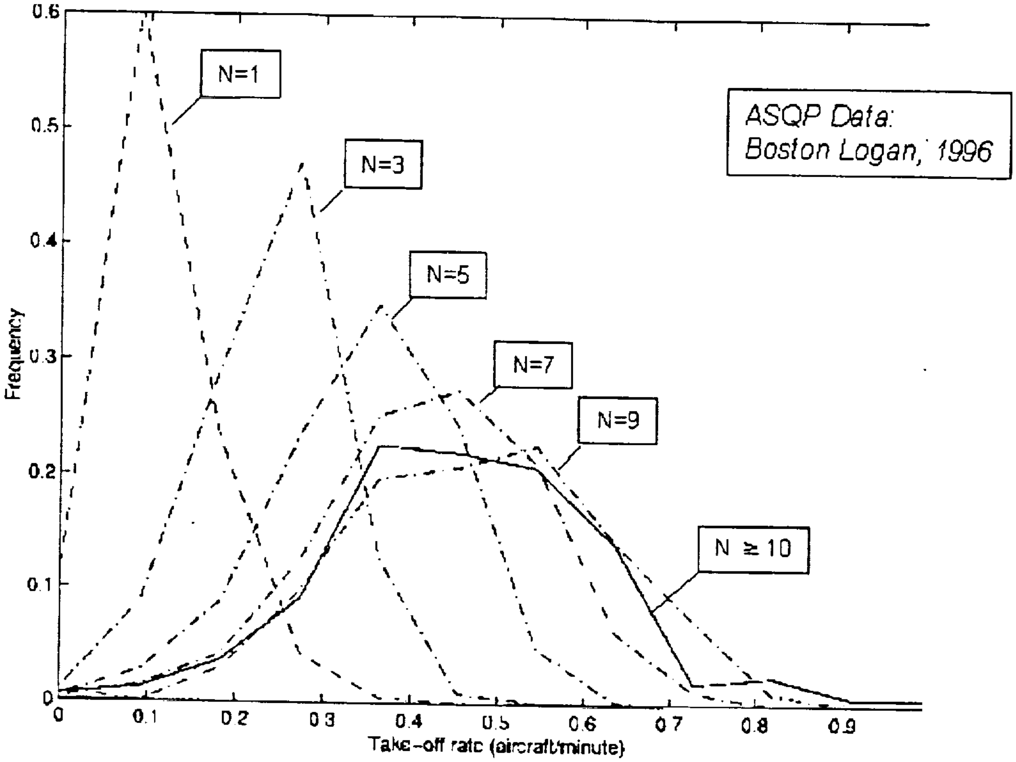

Figure 5: Evolution of $\bar{T}_5(t+6)$ as $N(t)$ varies (configuration 8)

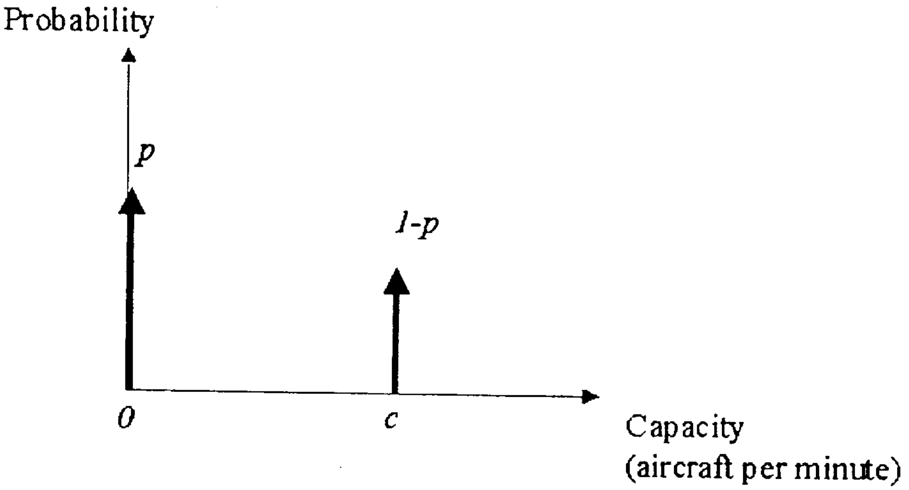
Probability
p
1-p
0
c
Capacity
(aircraft per minute)

Figure 6: Probability mass function of the departure capacity of the runway system model over one minute

$$0 \leq k \leq 2n+1 \; : \; \Pr\left(\bar{T}_n(t) = \frac{kc}{(2n+1)}\right) = \binom{2n+1}{k} \cdot (1-p)^k p^{(2n+1)-k} \tag{6}$$

The parameters p and c are chosen, for each configuration, so that the probability distribution in (6) matches the observed histograms of $\bar{T}_5(t+6)$ for high $N(t)$. For example, for configuration 8 table 3 shows that the values $p = 0.5$ and $c = 0.9$ give a good match.

Actual		Model	
Mean	Std.Dev.	Mean	Std.Dev.
0.48	0.14	0.45	.15

Table 3: Actual and model values of $\bar{T}_5(t+6)$ for high $N(t)$ under configuration 8 ($p = 0.5$ and $c = 0.9$)

3.3 Model validation

3.3.1 Principles of the model validation

A computer simulation of the model described in section 3 was used for validation. Each computer simulation run covers all the time periods in 1996 when the selected configuration was used.

Since the model will be used to evaluate queueing delays and test methods to reduce these delays, it should provide good estimates of:

- how many aircraft are waiting in runway queues (i.e. $RQ(t)$)
- how long these aircraft wait in runway queues (i.e. τ_{queue})

Since these values are not directly captured in the ASQP data, the model will be evaluated instead on how well it predicts:

- how many aircraft are on the taxiway system when flights push back (i.e. N_{PB})
- how long taxi-out times τ are, for various values of N_{PB}

3.3.2 Results for a high-capacity configuration

Figures 7, 8, 9 and tables 4 and 5 show validation results for configuration number 8. This configuration was in use for about 88200 minutes in 1996 (i.e.about 1470 hours), and represented 21500 pushbacks (which represents 24.4% of the total).

- figure 7 shows the "actual" distribution of N_{PB} that was observed in the ASQP database over 1996, along with the "simulated" distribution of N_{PB} averaged over 10 runs of the simulation. Table 4 presents the first two moments of the observed and simulated distributions.

Actual		Simulated	
Mean	Std.Dev.	Mean	Std.Dev.
3.88	2.07	3.64	2.00

Table 4: Comparison of actual and simulated N_{PB} distributions for configuration 8

- figure 8 presents the moving average of take-off rate $\bar{T}_5(t+6)$ as a function of $N(t)$. The curves represent the mean of the distribution of $\bar{T}_5(t+6)$ for each $N(t)$, and the vertical bars extend one standard deviation above and below the mean. The dashed lines are the observations from ASQP, while the solid lines are simulation results. The fit is very good, which means that the model reproduces very well the relationship between departures and N.

- figure 9 presents the distribution of τ for one airline over three ranges of N_{PB}:
  - light traffic ($N_{PB} \leq 2$)
  - medium traffic ($3 \leq N_{PB} \leq 7$)
  - heavy traffic ($N_{PB} \geq 8$)

As N_{PB} increases, the taxi-out time increases both in mean and in variance. The model provides good fits for $N_{PB} \leq 7$ but the fit is not as good for $N_{PB} \geq 8$.

Table 5 presents the first two moments of these distributions for the eight major airlines reported in the ASQP database at Boston Logan airport.

Almost all of the mean errors are quite small (well under 10%), but some mean errors are as high as 20%. This could reflect a small sample with little statistical significance (as is probably the case for the Delta Shuttle (DLS) mean error for $N_{PB} \geq 8$). Another explanation is that some airlines are subject to special constraints which are not included in our model (for instance, pushback and arrival operations are complex and highly coupled in an area of terminals B and C called the "horseshoe" [1]). The model tends to underestimate the standard deviation of the taxi-out distributions. This reflects the simple structure of the

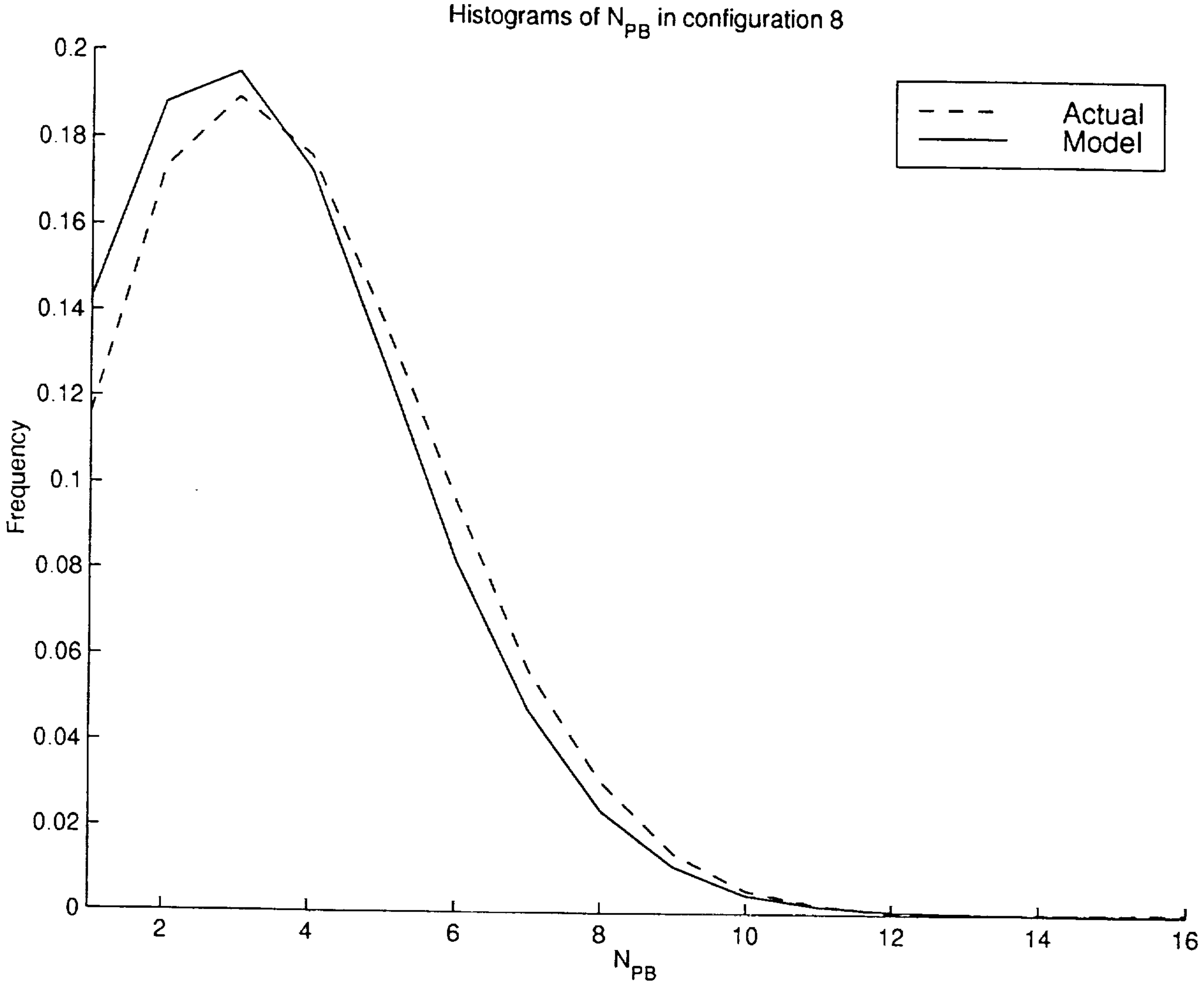

Figure 7: Actual and computer simulation model distributions of N_{PB} in configuration 8

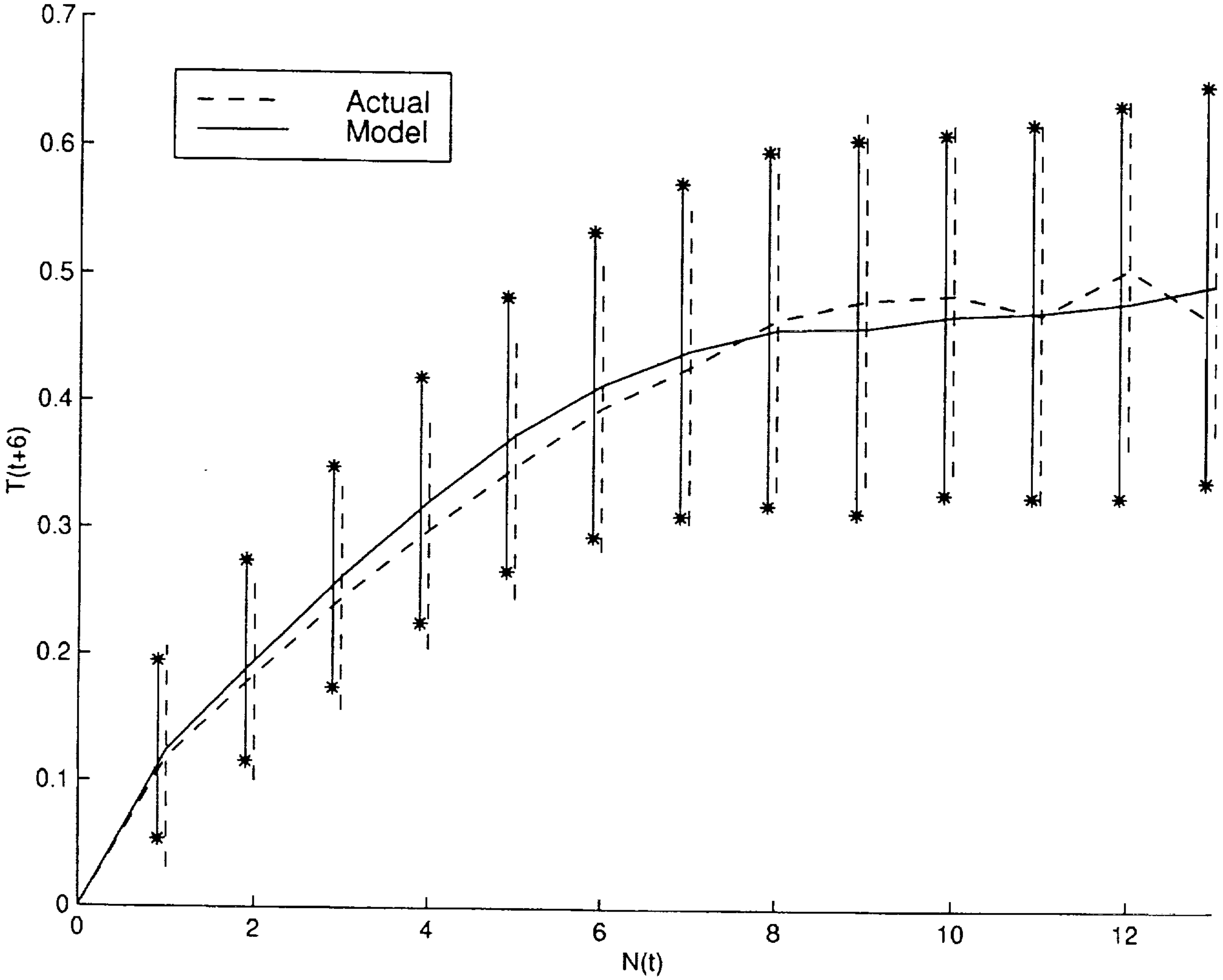

Figure 8: Moving average of take-off rate $\bar{T}_5(t+6)$ as a function of $N(t)$ for configuration 8

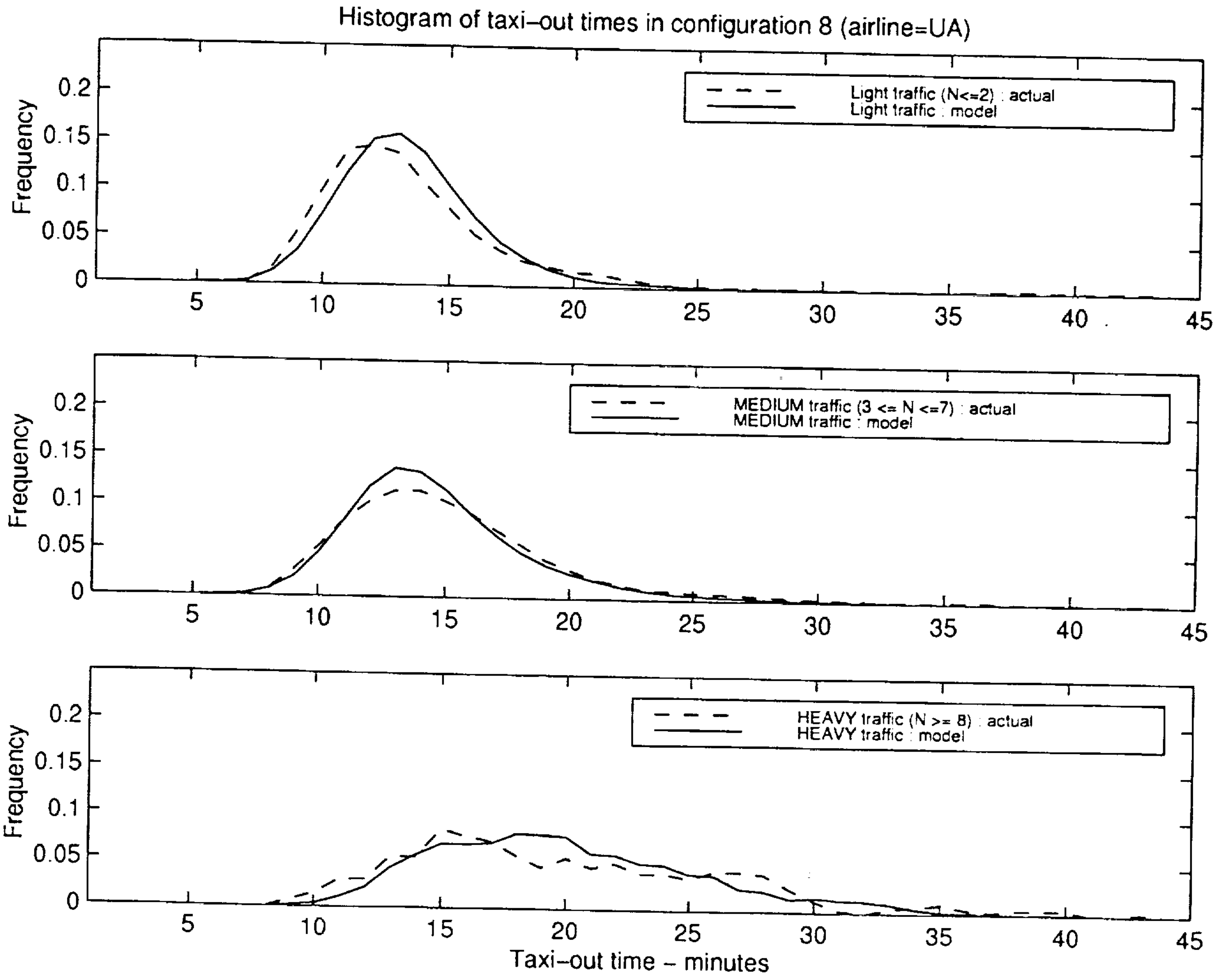

Figure 9: Taxi-out times in configuration 8

Light traffic ($N_{PB} \leq 2$)

Airline	Actual mean	Actual σ	Model mean	Model σ	Mean error (%)
AA	13.01	5.08	11.95	3.25	8
CO	12.97	4.12	12.89	3.08	1
DL	12.76	3.81	12.54	2.94	2
DLS	9.33	3.01	9.48	2.77	-2
NW	14.37	3.83	14.27	3.11	1
TW	14.16	4.12	13.94	3.21	2
UA	13.66	4.41	13.44	2.76	2
US	10.26	3.27	10.38	2.71	-1

Medium traffic ($3 \leq N_{PB} \leq 7$)

Airline	Actual mean	Actual σ	Model mean	Model σ	Mean error (%)
AA	15.5	6.05	13.47	3.87	13
CO	15.02	5.46	14.22	3.75	5
DL	14.89	4.83	13.92	3.6	7
DLS	11.21	4.55	11.09	3.91	1
NW	15.94	4.69	15.29	3.56	4
TW	16	5.71	14.95	3.63	7
UA	15.32	4.54	14.72	3.54	4
US	12.36	4.28	12.09	3.69	2

Heavy traffic ($N_{PB} \geq 8$)

Airline	Actual mean	Actual σ	Model mean	Model σ	Mean error (%)
AA	18.9	6.72	19.21	5.6	-2
CO	19.18	6.87	19.82	5.08	-3
DL	18.82	6.31	19.79	5.17	-5
DLS	14.12	5.14	17.01	5.54	-20
NW	19.26	5.57	21.2	5.41	-10
TW	20.02	7.11	20.06	5.24	0
UA	20.19	6.53	20.18	5.27	0
US	16.44	5.72	18.2	5.44	-11

Table 5: First two moments of taxi-out distributions in light, medium and heavy traffic in configuration 8

model, which does not fully account for some secondary factors: rare events (e.g. Ground Delay Programs), airspace constraints, differences in aircraft types, etc.

3.3.3 Validation results for a low-capacity configuration

Figures 10, 11, 12 and tables 6 and 7 show validation results for configuration number 9, which is a lower capacity configuration (see table 2: departures on runways 9 and 4R, and arrivals on 4R only). Configuration 9 was in use for 21800 minutes in 1996 (i.e. about 360 hours), and represented 3340 pushbacks (which represents 3.9% of the total). Since it is a low capacity configuration, it contributes significantly to runway queueing delays and thus noise and pollutant emissions.

- figure 10 shows the "actual" distribution of N_{PB} that was observed in the ASQP database over 1996, along with the "simulated" distribution of N_{PB} averaged over 10 runs of the simulation. Table 6 presents the first two moments of the observed and simulated distributions.

Actual		Simulated	
Mean	Std.Dev.	Mean	Std.Dev.
4.00	2.35	3.85	2.38

Table 6: Comparison of actual and simulated N_{PB} distributions for configuration 9

- figure 11 presents the moving average of take-off rate $\bar{T}_5(t+6)$ as a function of $N(t)$. The curves represent the mean of the distribution of $\bar{T}_5(t+6)$ for each $N(t)$, and the vertical bars extend one standard deviation above and below the mean. The dashed lines are the observations from ASQP, while the solid lines are simulation results. Again the match is quite good, which means that the model reproduces very well the relationship between departures and N.

- figure 12 present the distribution of τ over three ranges of N_{PB}:
  - light traffic ($N_{PB} \leq 2$)
  - medium traffic ($3 \leq N_{PB} \leq 7$)
  - heavy traffic ($N_{PB} \geq 8$)

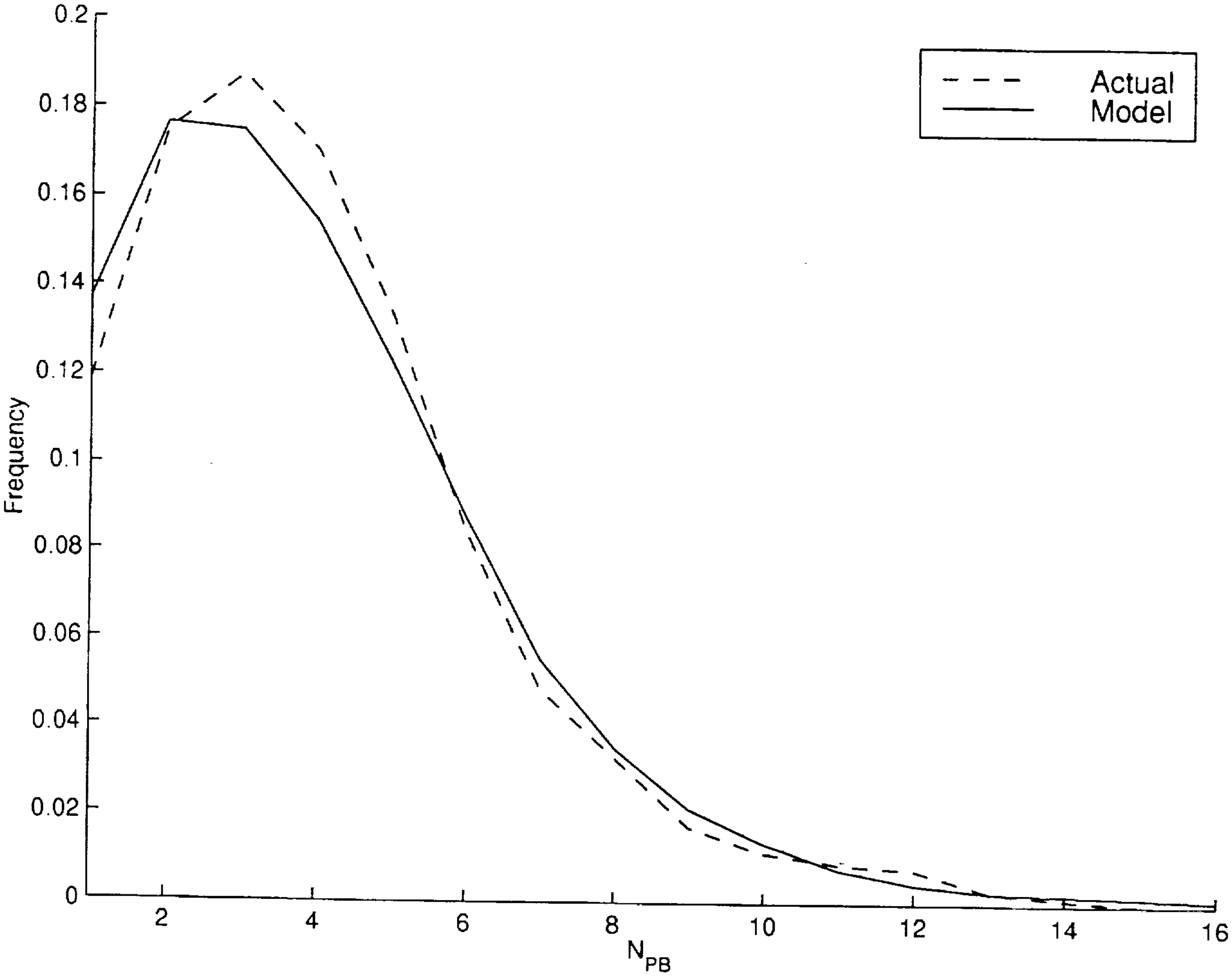

Figure 10: Actual and computer simulation model distributions of N_{PB} in configuration 9

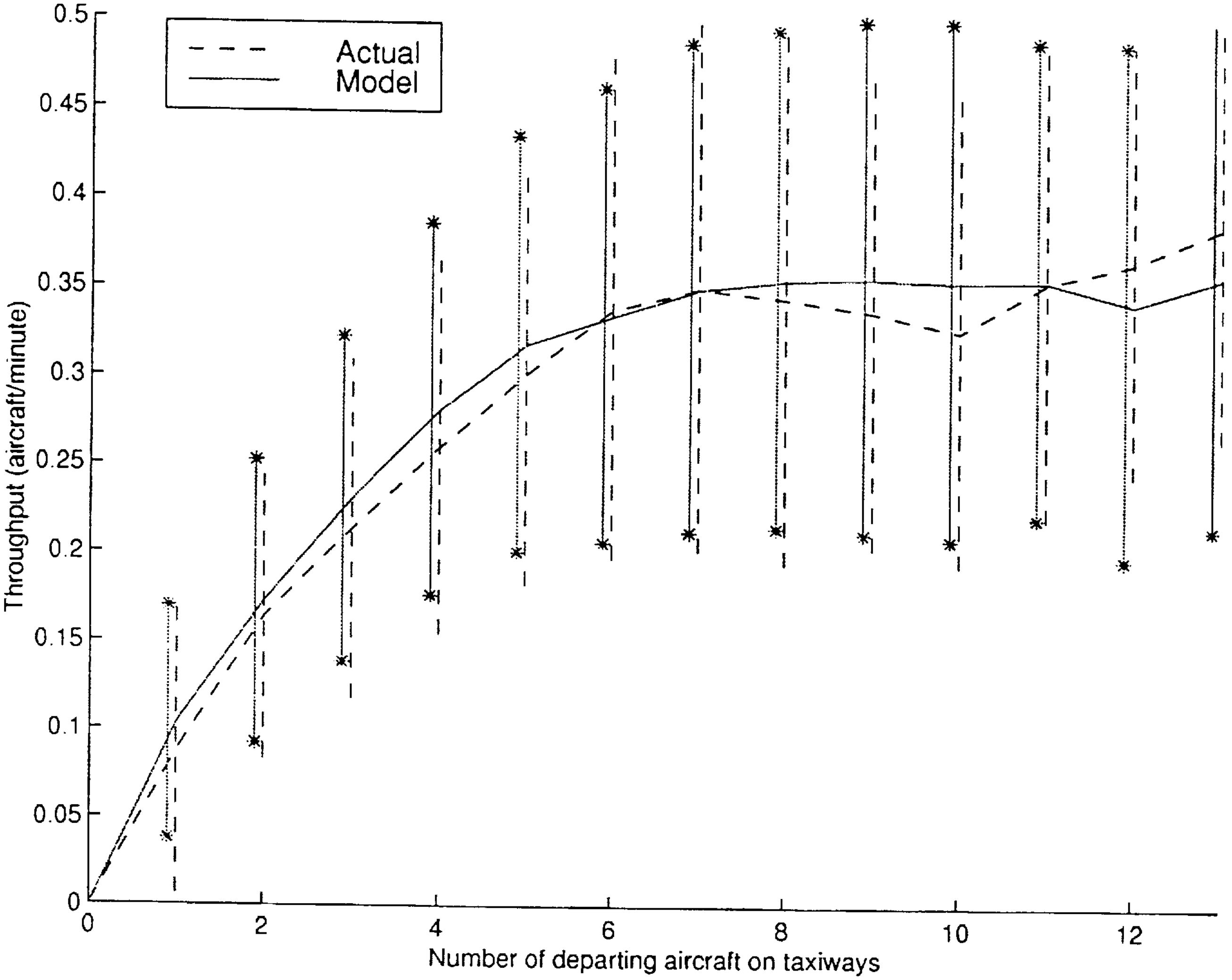

Figure 11: Actual and computer simulation model distributions of N_{PB} in configuration 9

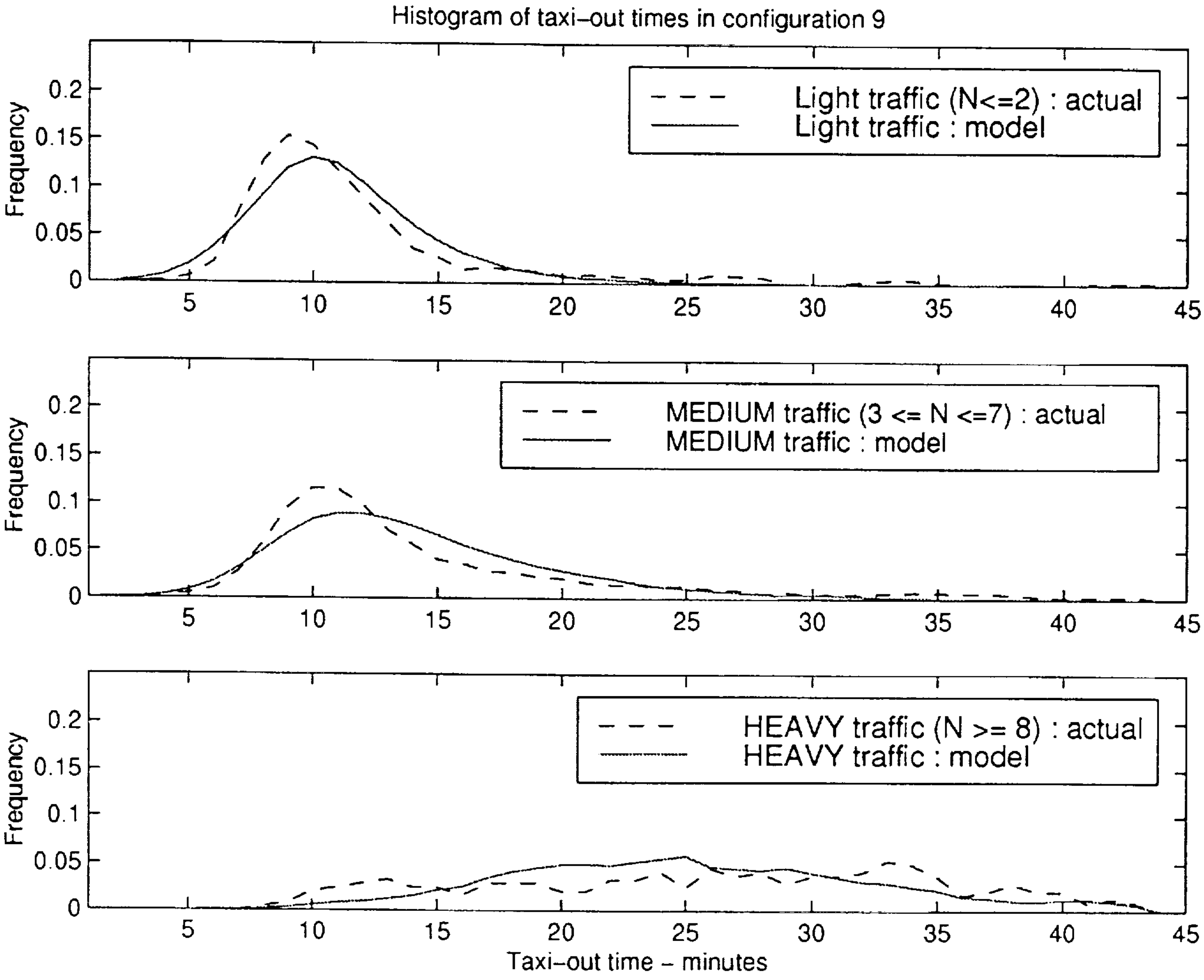

Figure 12: Taxi-out times in configuration 9

Again, it appears that as N_{PB} increases, the taxi-out time increases both in mean and in variance. In this low-capacity configuration, the variance in taxi-out time becomes very large for large values of N_{PB}. Possible explanations include:

- transient queueing: if the demand on the departure runway temporarily exceeds the reduced departure capacity, long queues can form quickly at the runway, causing a large increase in taxi-out time.
- unmodeled weather-related factors such as ground delay programs.

Table 7 presents the first two moments of these distributions for the nine major airlines reported in the ASQP database at Boston Logan airport.

The mean errors are larger than in the case of configuration 8, mostly because of the increased variability of operations under low-capacity, bad weather scenarios. Note in particular the samples are about 7 times smaller than in the case of configuration 8 (because configuration 9 is not used as often) which could explain some of the high mean errors.

Light traffic ($N_{PB} \leq 2$)

Airline	Actual mean	Actual σ	Model mean	Model σ	Mean error (%)
AA	14.83	7.27	13.17	4.33	11
CO	14.02	5.17	13.05	3.98	7
DL	14.32	5.94	13.84	4.22	3
DLS	10.83	6.42	9.73	3.07	10
NW	17.1	7.32	14.16	3.6	17
TW	13.68	3.6	14.02	3.78	-2
UA	14.06	3.44	14	3.54	0
US	11.67	5.18	10.91	3.29	7

Medium traffic ($3 \leq N_{PB} \leq 7$)

Airline	Actual mean	Actual σ	Model mean	Model σ	Mean error (%)
AA	15.97	6.67	16.57	6.04	-4
CO	18.13	7.7	16.26	5.64	10
DL	16.41	7.18	16.95	5.76	-3
DLS	15.46	8.83	11.94	4.93	23
NW	18.03	7.56	16.96	5.38	6
TW	18.06	7.7	17.15	5.65	5
UA	16.24	5.41	16.97	5.24	-4
US	14.73	7.41	14.25	5.43	3

Heavy traffic ($N_{PB} \geq 8$)

Airline	Actual mean	Actual σ	Model mean	Model σ	Mean error (%)
AA	20.42	4.85	26.67	7.43	-31
CO	25.41	7.99	26.61	7.35	-5
DL	22.67	9.23	26.89	7.04	-19
DLS	0	0	0	0	0
NW	21.8	5.23	27.12	6.29	-24
TW	0	0	0	0	0
UA	21.32	6.05	27.55	6.99	-29
US	26.14	8.98	24.88	7.07	5

Table 7: First two moments of taxi-out distributions in light, medium and heavy traffic in configuration 9

4 Control of the Departure Process

Subsection 4.1 introduces the two major incentives for reducing runway queueing times:

- reductions in direct operating costs
- reductions in environmental costs.

Subsection 4.2 considers some of the constraints that must be taken into account in the formulation of departure process control schemes.

Subsection 4.3 presents the results of the quantitative evaluation of simple departure process control schemes. This evaluation was conducted using the model developed in this paper.

4.1 Motivation: Cost of queueing delays vs gate delays

4.1.1 Direct operating costs

U.S. airlines are required to report Direct Operating Costs (DOC) data to the Department of Transportation ("Form 41"[11]). Even though this data can be affected by variability in accounting methods, it provides reasonable estimates of DOC.

The major components of DOC are:

- Fuel cost
- Crew cost
- Maintenance costs

Note that marginal crew and maintenance costs are difficult to estimate because of the complex overhead costs that are associated with these components of airline operations. Estimated DOC values are shown on table 8 for three different aircraft types: medium jets (e.g. Boeing 737), large jets (e.g. Boeing 757 and 767) and heavy jets (e.g. DC-10 and Boeing 747). These estimates are based on 1992 and 1995 data (from [12] and [13]) and are averaged over all major U.S. airlines.

Table 8 shows that each minute of runway queue delay transferred to the gates could result in DOC savings of \$10.5 to \$48 depending on the aircraft type. Table 9 shows an estimate of the jet aircraft departure traffic

	$/min. at gate			**$/min. in queue**		
Jet aircraft type	*Medium*	*Large*	*Heavy*	*Medium*	*Large*	*Heavy*
Fuel	0	0	0	2	4	9
Flight crew	2.5	4.5	6	6	12	20
Maintenance	0	0	0	5	9	25
Total	**2.5**	**4.5**	**6**	**13**	**25**	**54**

Table 8: DOC estimates at the gate and in runway queue

mix at Boston Logan (this estimate was obtained from Enhanced Traffic Management System (ETMS) data collected in June 1998). Combining the data in table 8 and 9 yields an average cost saving of $ 15.4 for each minute of runway queue delay transferred to the gates.

Jet aircraft type	**% of Boston jet operations**
Medium	65
Large	30
Heavy	5

Table 9: Mix of jet aircraft departure operations at Boston Logan in June 1998

4.1.2 Environmental costs

Airports are sensitive areas in terms of pollution. The residents of nearby neighborhoods suffer from noise and pollutants generated by the airport. Among the pollutants emitted by aircraft are [14]:

- Nitrogen oxides (NOx), which play a role in acid rains and are precursors of particulate matter (which reduce visibility) and low-level ozone (a highly reactive gas which is a component of smog and affects human pulmonary and respiratory health).

- Unburnt hydrocarbons (HC) and carbon monoxide (CO), especially at low engine power settings such as in taxi-out mode.

- Sulfur oxides (SOx), which play a role in acid rain.

- Particulate Matter (PM), especially at low power settings such as in taxi-out mode.

A study for the Washington state Department of Ecology estimated that the contribution of aircraft queueing on the taxiways at Seattle-Tacoma airport constitutes a significant percentage of surface operations pollutant emissions, and in particular:

- 20 % of NOx emissions

- 50 % of SOx emissions

- 40% of PM emissions

Table 10 shows engine emission characteristics for common aircraft and engine types, at the idle power setting that is typically used during the runway queueing [15]. This table can be used to estimate the environmental cost of jets queueing on the airport taxiways. The last column shows, for each aircraft/engine combination, the percentage of jet departure operations it represented at Boston Logan in June 1998, as found in the Enhanced Traffic Management System (ETMS) database. The last row is based on these percentages and shows the average emissions for one minute of jet aircraft runway queueing at Boston Logan airport:

Aircraft/engine	**Emissions (g/min)**			**% of Boston jet operations**
	HC	CO	NOx	
B-727 / JT8D	74.30	336.73	69.06	13.3
DC-9 / JT8D	49.53	224.49	46.04	11.2
B-737 / JT8D	49.53	224.49	46.04	4.3
B-737 / CFM56-3-B1	31.19	470.59	53.35	11.4
MD-80 / JT8D-209	63.01	220.47	54.73	16.2
A320 / V2500-A1	3.27	115.47	87.94	6.9
B-757 / PW2037	38.24	390.85	74.45	19.4
A300 / PW4060	42.43	519.38	125.24	3.0
B-767 / CF6-80C2A2	237.69	1043.51	89.59	3.7
DC-10 / CF6-50C	843.66	2391.66	139.32	1.6
B-747 / CF6-80C2A2	988.85	2803.25	163.30	2.0
Weighted average for Boston	*82.31*	*401.26*	*64.35*	

Table 10: Jet engine aircraft emissions

Note: the Environmental Protection Agency (EPA) and the Federal Aviation Administration (FAA) are also considering other measures to reduce airport operations pollutant emissions:

- reducing engine pollutants emission rate: the engine emission standards developed and recommended by ICAO and adopted by the EPA reflect the progress made in emission reduction technology [16].

- converting Ground Support Equipment (GSE), such as fuel trucks and cargo loading vehicles, to "clean" alternative fuels and reducing Auxiliary Power Unit (APU) usage. However, GSE and APU usage typically constitute only 10 percent of the combustion pollutants emissions at an airport, while aircraft engines contribute 45 percent and ground access vehicles contribute the remaining 45 percent.

4.2 Guiding principles for control concepts

Many airport surface operations control schemes have been envisioned, but few have emphasized essential human factors considerations (in particular, see [1] on the lessons to be drawn from the Departure Sequencing Engineering and Development Model program). Airport operations are almost entirely monitored and controlled by human operators. Workflow and workload constraints should be considered whenever the feasibility of a new airport control scheme is evaluated. Any major change to the airport control procedures would be difficult to study in-situ. Indeed controllers are unlikely to accept any new procedures before they feel it has been proven that they not only work better than the current ones in all circumstances, but also maintain or improve safety and do not generate excessive workload or radical changes in controller roles and training.

For example, control schemes centered on sequencing should take into account the fact that aircraft sequencing might require more real-time observations of the position of the aircraft on the taxiway system than are currently captured, and more interventions of the controllers to ensure the sequence is realized at the runway threshold (indeed establishing the sequence through pushback clearances is not enough due to large uncertainties in pushback and taxi times [1]). These additional observations and interventions entail additional workload for all airport controllers.

Thus it appears that the only control schemes which can bring immediate benefits are the ones which don't require changing the airport control system extensively but rather help controllers take better decisions in their current work process.

4.3 Quantitative evaluation of departure process control schemes

An easily applicable control concept would consist in holding selected aircraft at their gates to reduce the runway queue in low capacity configurations. A complete evaluation of such a "gate holding" control concept should consider how it would interact with the current Airport Tower control actions. However a conservative performance evaluation of the control concept can be obtained if it is implemented as a simple gate queue immediately downstream from the Airport Tower controllers.

Define:

$GQ(t)$ = the number of aircraft which have been cleared by the airport tower controllers at or before period t but are still being held at the gate by at the end of period t.

Figure 13 presents the resulting "evaluation" model.

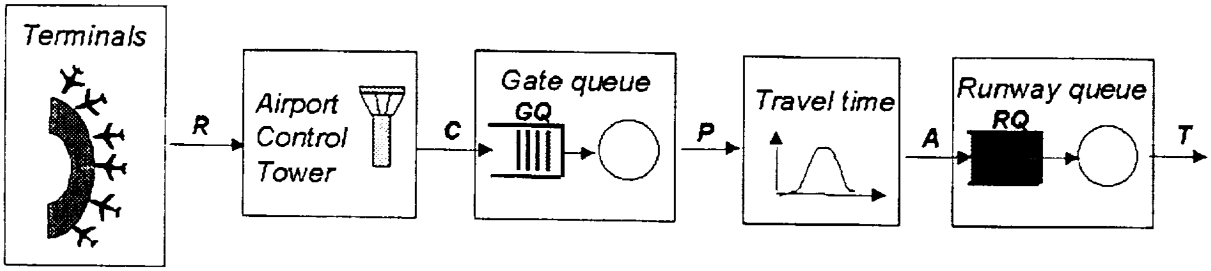

Figure 13: Structure of the departure process model for control scheme evaluation

Note that since it is assumed that the Airport Tower control actions are unaffected by the implementation of the gate queue downstream, $C(t)$ is still simply the number of actual pushbacks recorded during period t in the ASQP data.

In addition to following the equations (1) through (3) with the parameters determined in section 3, the evaluation model follows the gate queue balance equation:

$$GQ(t) = GQ(t-1) + C(t) - P(t) \tag{7}$$

The number $P(t)$ of aircraft which are released from the gate queue and push back during period t is governed by the specific gate holding algorithm that is to be evaluated. Paragraphs 4.3.1 and 4.3.2 present examples of such gate holding algorithms.

4.3.1 Quantitative evaluation of a state-feedback gate holding scheme

An easily applicable gate holding scheme can be inferred from the departure dynamics shown on figure 8 and 11. It appears on these figures that the throughput of the runway does not improve much when N becomes larger than a saturation value N_{sat} (e.g. $N_{sat} \approx 6$ in configuration 9). Indeed $N > N_{sat}$ typically corresponds to periods when the runway queue is not empty and thus when the runway is operating at maximum capacity. Allowing N to become larger than N_{sat} results in more aircraft in queue at the runway with little increase in throughput. These observations suggest a control scheme in which aircraft are held at their gates whenever N exceeds some threshold value N_c. This amounts to controlling the number of pushbacks $P(t)$ by setting:

$$P(t) = \min(\max(N_c(t) - N(t), 0), GQ(t-1) + C(t)) \tag{8}$$

This control scheme would be easily implemented by human controllers at an airport like Boston Logan, since $N(t)$ can be observed in the tower as the number of flight strips on the ground controller's rack. It could also be part of a larger scale conceptual control architecture as described in [17] and [18]. Figure 14 shows the effect of the control scheme for different values of N_c, under configuration 9. It was obtained through simulation using the model shown on figure 13. The simulation was run for all the time periods of 1996 when configuration 9 was in effect, using the actual departure demand found in the ASQP database but implementing the control scheme expressed by (8). The gate holding delay and runway queueing delay of each flight were recorded. The total gate delay and runway delay over all these flights is shown on figure 14.

As N_c becomes smaller than N_{sat}, the loss of runway throughput causes an increase in total delay. But for $N_c \geq N_{sat}$, this control scheme simply replaces runway queueing time with gate delay with little impact on runway throughput. Naturally, gate delay is less costly than runway queueing time, mostly because the aircraft engines are not running while the aircraft is at the gate (see subsection 4.1). For $N_c = 7$, the reduction in runway queueing time would be around 2300 minutes (i.e. 11.5 %), over the 360 hours during which configuration 9 was in use. Using the engine emission data and jet traffic mix from table 10, this reduction in runway queueing time would translate into the following reductions in pollutant emissions:

- HC: 189 kg
- CO: 922 kg
- NOx: 148 kg

The direct operating cost savings can be computed using tables 8 and 9. They amount to \$ 35,400. Note that this number represents savings under configuration 9 alone, i.e. 3.9% of the jet departure operations. Assuming that similar queueing time reductions could be obtained for the remaining 15.1% of jet operations in low capacity configurations, (see table 2) the direct cost savings would amount to \$ 170,000 per year.

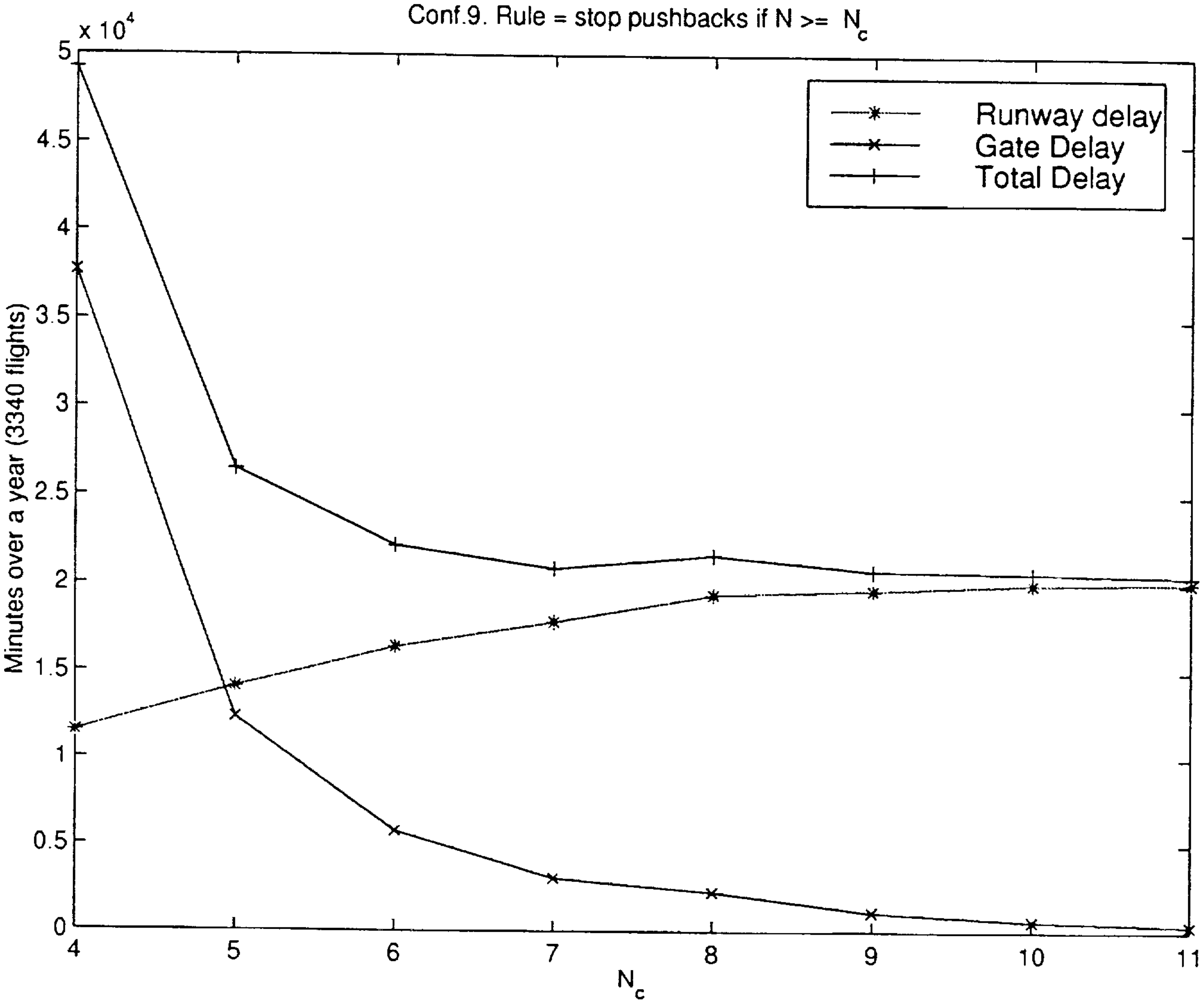

Figure 14: Effect of holding aircraft at the gates when $N \geq N_c$ in configuration 9 - using actual 1996 demand data

Additional savings could be obtained in the 81% of higher capacity jet operations, and by taking into account turboprop operations (which represent up to 55% of departures at Boston Logan airport).

Note that this gate holding control scheme would only work is enough gate capacity was available to accommodate the aircraft being held. Figure 15 shows how often one of the major airlines at Boston Logan airport (operating more than 10 gates) would reach its maximum gate capacity, over the configuration 9 operations of 1996, for various values of N_c. For $N_c = 7$, the airline would very rarely reach its maximum gate capacity (only about 14 minutes over the 360 hours of configuration 9 operations in 1996). Note that in the rare cases when it would reach its maximum gate capacity, the simulation showed that only one additional gate would be required. Similar results have been obtained for the other airlines operating at Boston Logan.

4.3.2 Quantitative evaluation of a predictor-based gate holding scheme

The control scheme described in subsection 4.3 relies exclusively on the observation of the current state of the airport (in particular $N(t)$, the number of departing aircraft on the taxiway system). It does not take into account future departure demand, or the future evolution of the runway departure capacity (e.g. due to changes in the arrival rate). A control scheme which would use estimates of future departure demand and runway capacity in addition to the current state of the airport should result in an additional reduction in runway queueing times. Paragraphs 4.3.2 and 4.3.2 consider the availability of data on future departure demand and runway capacity. Paragraph 4.3.2 presents a control scheme architecture, based on departure slot allocation, which would take advantage of these data. Paragraph 4.3.2 presents a simple slot allocation algorithm, and an estimate of the reduction in runway queueing times it could bring in the case of Boston Logan.

Availability of departure demand information. In current operations, the only future departure demand information available to the FAA Air Traffic Control Tower (ATCT) is the Flight Information Management System (FIMS) maintained by the airlines to inform their passengers of planned departure times. FIMS is not always accurate since it does not instantly reflect some sources of potential departure delays:

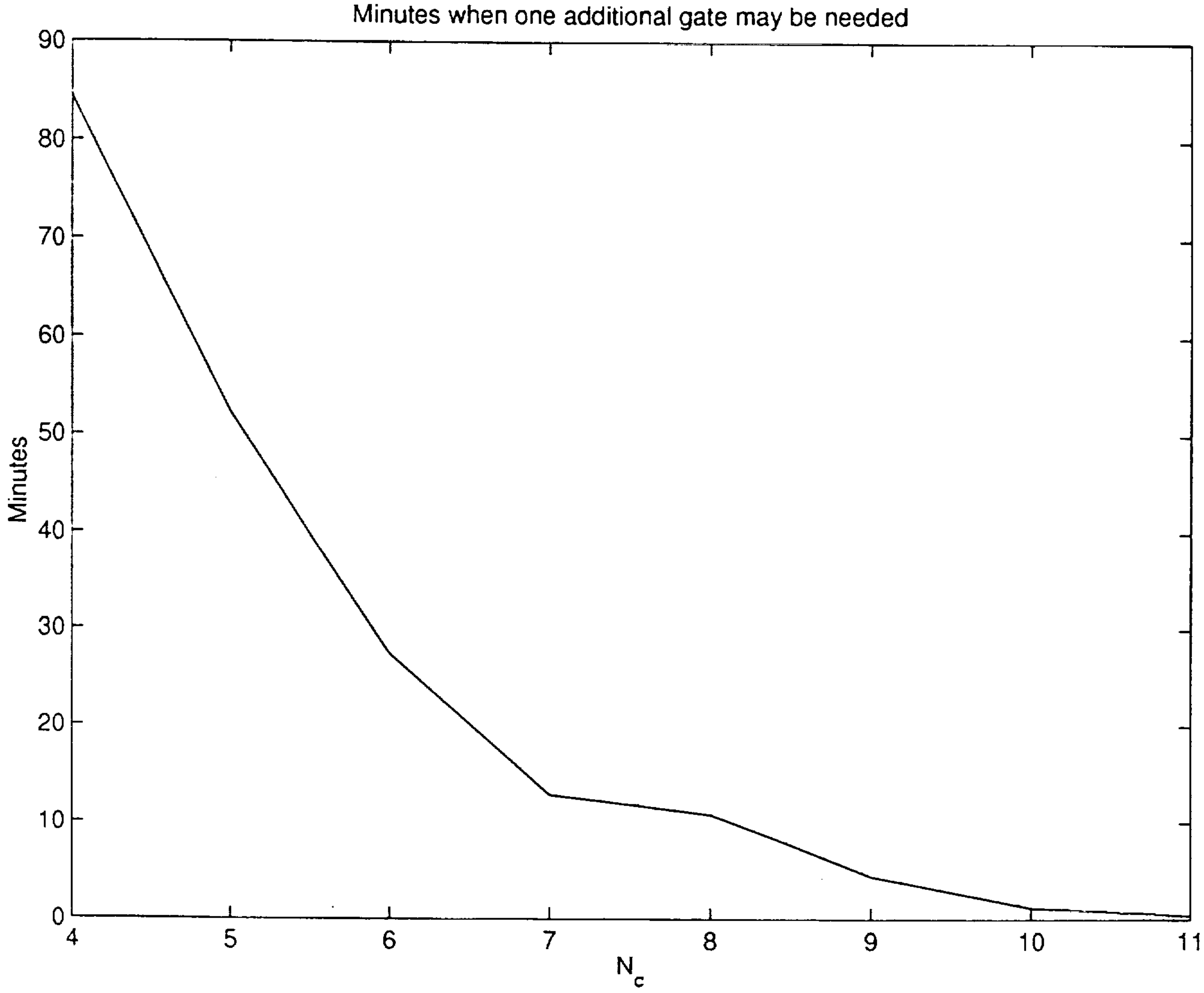

Figure 15: Additional gate capacity needed to control N around N_c by one airline under configuration 9

- late inbound resources (aircraft, crew, flight attendants)
- departure holds to allow passenger connections
- delays in preparing the aircraft for departure (passenger boarding, baggage and cargo loading, catering, etc.)
- aircraft mechanical problems currently under investigation ("flights on decision")

It is however a good indication of future demand on a short time scale.

It can be envisioned that more departure demand information would become available in the future. Indeed, since the early days of the FAA - Airlines Data Exchange (FADE) program, significant progress has been made in the definition and implementation of Collaborative Decision-Making (CDM) procedures, which allow the airlines and the FAA to exchange more accurate information on future departure demand in the context of Ground Delay Programs (GDP). Departure demand could then be predicted more accurately on longer time scales.

Availability of runway departure capacity information. The departure capacity of a runway system can be directly affected by many factors, including:

- weather conditions
- departure airspace constraints
- arrivals

The weather conditions can usually be forecasted with satisfying accuracy 30 minutes in the future (except in drifting fog conditions). Airspace constraints also vary slowly and are quite predictable.

In current operations, the future arrivals at an airport are not known with good accuracy, due to uncertainties in the timing of aircraft descent profiles and approach paths. However, the new Center-TRACON automation system (CTAS) has been shown to improve significantly the accuracy of arrival time predictions [19] [20]. It appears possible to predict future arrivals up to 15 minutes in advance with an accuracy of 30 seconds.

Departure slot allocation architecture. The concept of landing slot allocation is used extensively at major congested airports such as Chicago O'Hare and London Heathrow, and at smaller airports in case of ground delay programs. The same concept can be applied to departure operations. However, a strict application of the concept would require air traffic control tower controllers to actively control taxiing aircraft to ensure that they arrive in the correct order and at the correct times to comply with the slot allocation. This would make the testing and implementation of the concept difficult and costly. In order to minimize disruptions to the current controller work processes , the slot allocation process could be limited to determining optimal pushback times. Aircraft would be held at the gate until a desired pushback time which should take them to the runway in time for their take-off slot. After pushback, controllers would not be required to ensure that aircraft are exactly complying with the slot allocation. The price to pay for this simplicity is an increased vulnerability to uncertainties in taxi times.

Define H to be the time horizon for predictions and slot allocations. Based on paragraphs 4.3.2 and 4.3.2, a reasonable value for H would be 20 minutes. A simple departure slot control architecture could be used to implement this concept:

- *Step 1a. Prediction of runway capacity: the future runway capacity is predicted over* $(t, t + H)$ *taking into account weather, airspace constraints, arrivals, etc. as outlined in paragraph 4.3.2.*

- *Step 1b. Prediction of runway arrival times: the times at which currently taxiing aircraft will arrive at the runway and the remaining departure runway capacity are estimated.*

- *Step 1c. Prediction of departure demand: based on the published schedule and updates from the airline control centers, a "departure pool" consisting of the aircraft which will request a departure over* $(t, t + H)$ *is estimated.*

- *Step 2. Take-off slot allocation: an algorithm allocates the available runway departure capacity to aircraft in the departure pool. The algorithm should try to minimize runway queuing times while respecting some key constraints (e.g. in general, an aircraft cannot leave its gate before its published departure time) and fairness rules (e.g. first come first served).*

- *Step 3. Selection of pushback times: a pushback time is selected for each aircraft in the departure pool* *which has been assigned a slot, taking into account the time it will take for the aircraft to reach the runway under current airport conditions.*

Notes:

- the slot allocation algorithm should take into account the uncertainty arising in the runway departure capacity and demand predictions.
- the selected pushback times should also take into account the uncertainty in the travel time to the runway.
- for a more detailed analysis of the departure process and control points, the reader is referred to [18].

Departure slot allocation algorithm. Many algorithms (or combinations thereof) can be used to optimize to slot allocation process:

- Heuristics
- Mathematical programming
- Dynamic programming (or approximate dynamic programming)

A simple heuristic can be used to obtain a conservative estimate of potential benefits of the departure slot allocation concept. This heuristic is an implementation of the architecture described in paragraph 4.3.2.

- *Step 1a: the predicted runway departure capacity is taken to be constant over* $(t, t + H)$ *and equal to the average capacity observed in this configuration under high taxiway loading (e.g under configuration 9, figure 11 shows that the average departure capacity under high taxiway loading is around 0.35 aircraft/minute).*
- *Step 1b: the runway arrival time of each taxiing aircraft is estimated by adding to its pushback time the average taxi time for its airline in this particular runway configuration (see paragraph 3.2.2).*
- *Step 1c: future departure requests are assumed to be known exactly over* $(t, t + H)$.

- *Step 2. The slot allocation algorithm spreads the departure demand to ensure that the predicted runway queue over* $(t, t+H)$ *does not exceed a target runway buffer* RQ_c*. Slots are allocated according to the following variation of the first come first served rule: out of all the aircraft in the departure pool which could be assigned to the take-off slot, the aircraft that is actually assigned is the one with the earliest departure request time.*

Figure 16 shows the simulated effects of this simple slot control scheme for different values of the target runway buffer RQ_c, under configuration 9 in 1996. It was obtained in the same way as figure 14, i.e. using the evaluation model shown on figure 13. The time horizon H was chosen to be 20 minutes.

As RQ_c decreases, the runway queueing time is reduced while the gate queueing time increases. However, the total queueing time increases more rapidly than under the state feedback control scheme presented in paragraph 4.3.1. In particular, to achieve a reduction of the runway queueing time of 11.4%, the simple slot allocation algorithm causes an increase of 8.8% in total queueing time, while the state feedback control scheme only causes a 4% increase. The relatively poor performance of the simple slot control algorithm can be attributed to the large uncertainties in travel times and departure capacity that were not taken into account. The observation of additional airport operations data (such as arrivals and turboprop operations) should reduce these uncertainties and improve the performance of slot allocation algorithms.

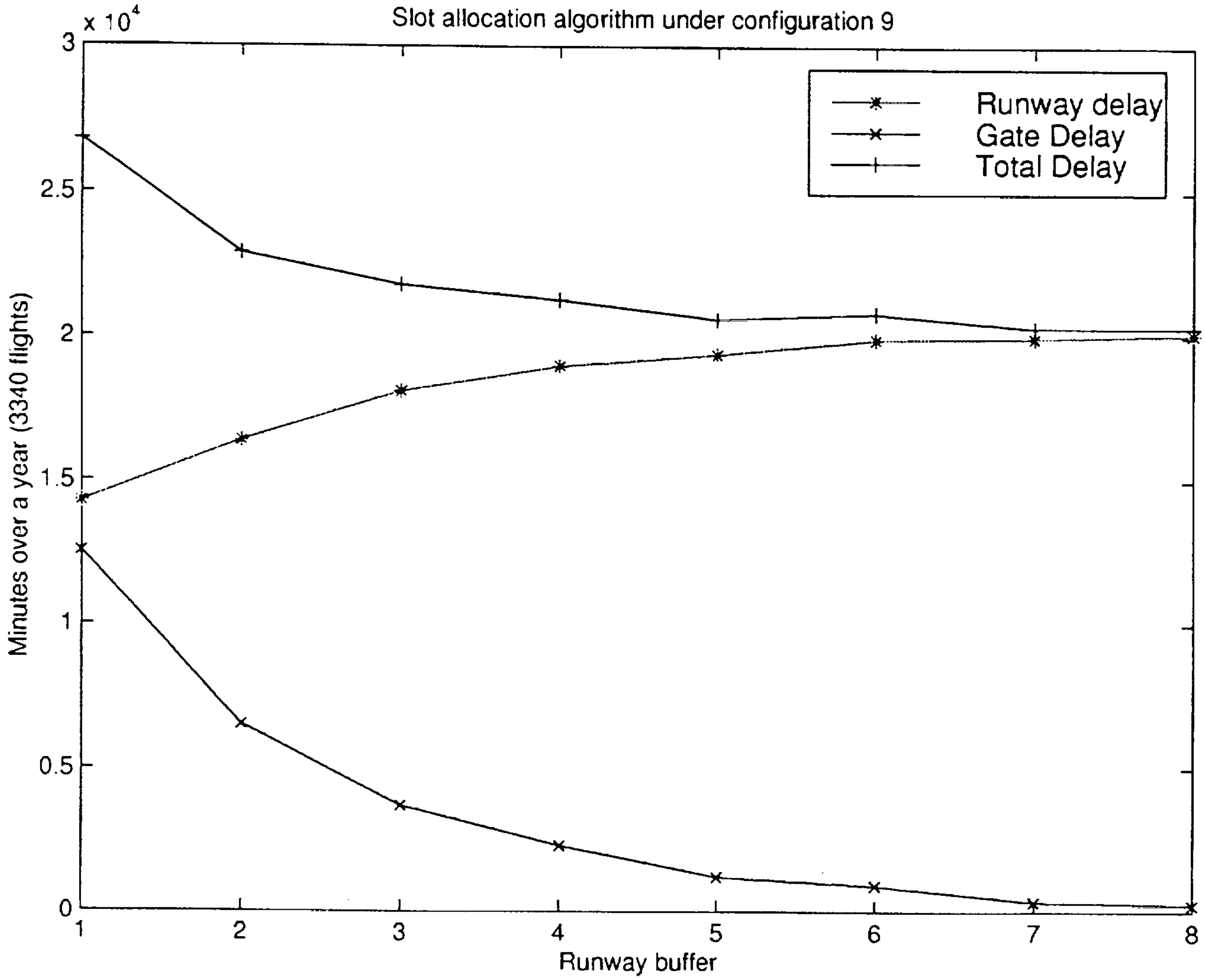

Figure 16: Effect of a simple slot control scheme in configuration 9 - using actual 1996 demand data

5 Conclusion

In this paper, we have considered the problem of modeling the departure process at a busy airport for the purpose of alleviating surface congestion. Our experimental investigation has allowed us to provide a simple, yet extensively validated dynamical queueing model of the departure process. Preliminary investigations show that active control strategies on this model can reduce congestion on the airport surface using aircraft gate holding. These strategies allow a reduction in direct operating costs and environmental costs without increasing total delay significantly. Their implementation would be compatible with the current airport operations and human control structure. Further research will combine aircraft departure control with arrivals control, with the intent to improve the overall airport efficiency. Further efficiency will also be gained via the investigation of more advanced control laws.

6 Acknowledgments

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Nationwide Benefits of N Control

The effect of N Control was evaluated via an analysis of ASQP data for the top 100 airports in the US. In this analysis, the following parameters were recorded for each departure: (a) the number of aircraft taxiing out immediately after the departure pushed-back from the gate, (b) the taxi-out time, and (c) the number of aircraft that takeoff while the aircraft is taxiing out. Although this analysis was not as detailed as the analysis by Pujet, the independence of each configuration at an airport is sufficient to guarantee that the composite analysis will be a superposition of the results for individual configurations. Figures 1 to 3 show the composite results for Newark International Airport (EWR), the airport that was found to show the greatest benefits from N Control.

Figure 1 shows the taxi out time versus the number of aircraft taxiing out. As the figure shows, although the taxi out time is initially insensitive to the number of aircraft taxiing out, the taxi time rises significantly once the number of aircraft taxiing out is greater than ten.

Figure 2 shows the number of aircraft that took off while a departure was taxiing out versus the number of aircraft taxiing out. As is to be expected, the relationship is represented by a straight line since, although there is swapping of aircraft between push back and takeoff, on average aircraft depart in the order they push back from the gate.

Figure 3 shows the takeoff rate (the number of aircraft taking off per minute) versus the number of aircraft taxiing out. As the figure shows, the takeoff rate saturates when the number of aircraft taxiing out increases above ten.

Figure 4 shows the benefits of N Control in number of minutes of taxi out time saved as a function of the maximum number of aircraft allowed to taxi out. As the figure shows, if the number of aircraft allowed to taxi out is limited to eleven, an annual savings of over 385,000 can be achieved.

Table 1 shows the desired N Control and savings that can be achieved at the top 40 airports in the US (ranked by the number of operations). As the table shows, there are some airports with savings that are much greater than their ranking in terms of annual operations would suggest. A comparison of the rank in terms of operations and the rank in terms of benefits shows that there are four airports (EWR, PHL, JFK, LGA) that show significant levels of taxi out inefficiency. For the top 100 airports, the total annual nationwide benefit of N Control is approximately 1.4 million minutes.

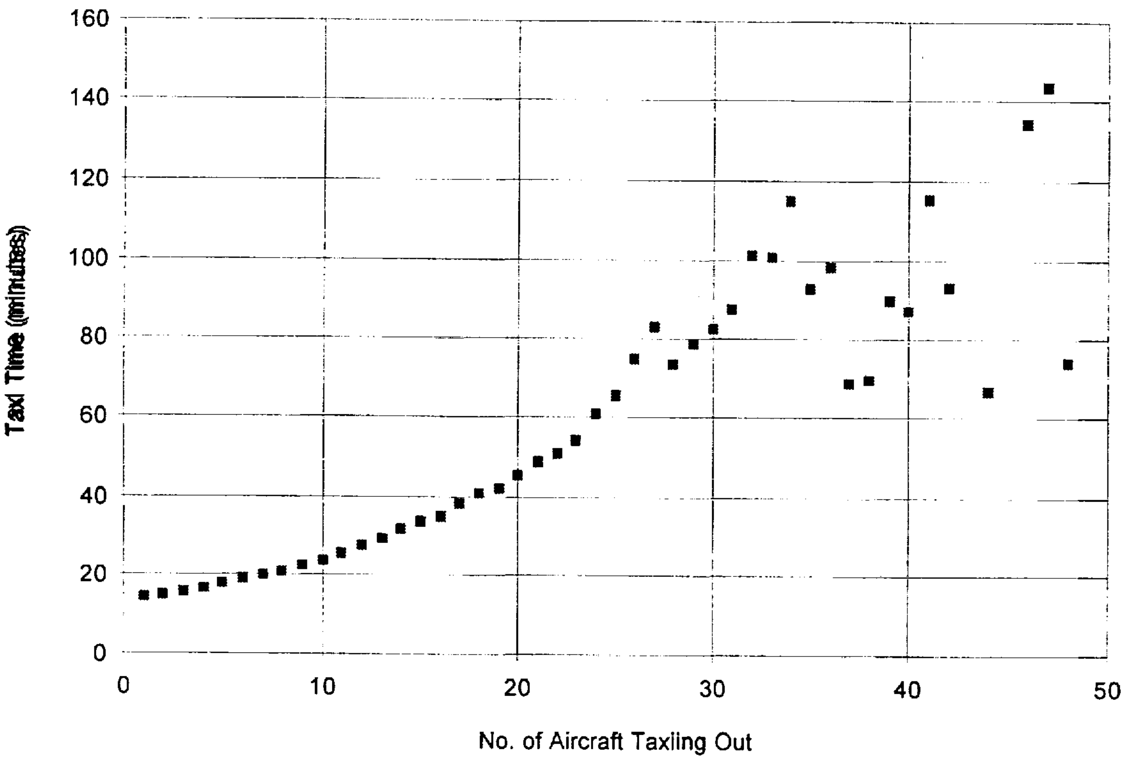

Figure 1: Taxi out time versus number of aircraft taxiing out

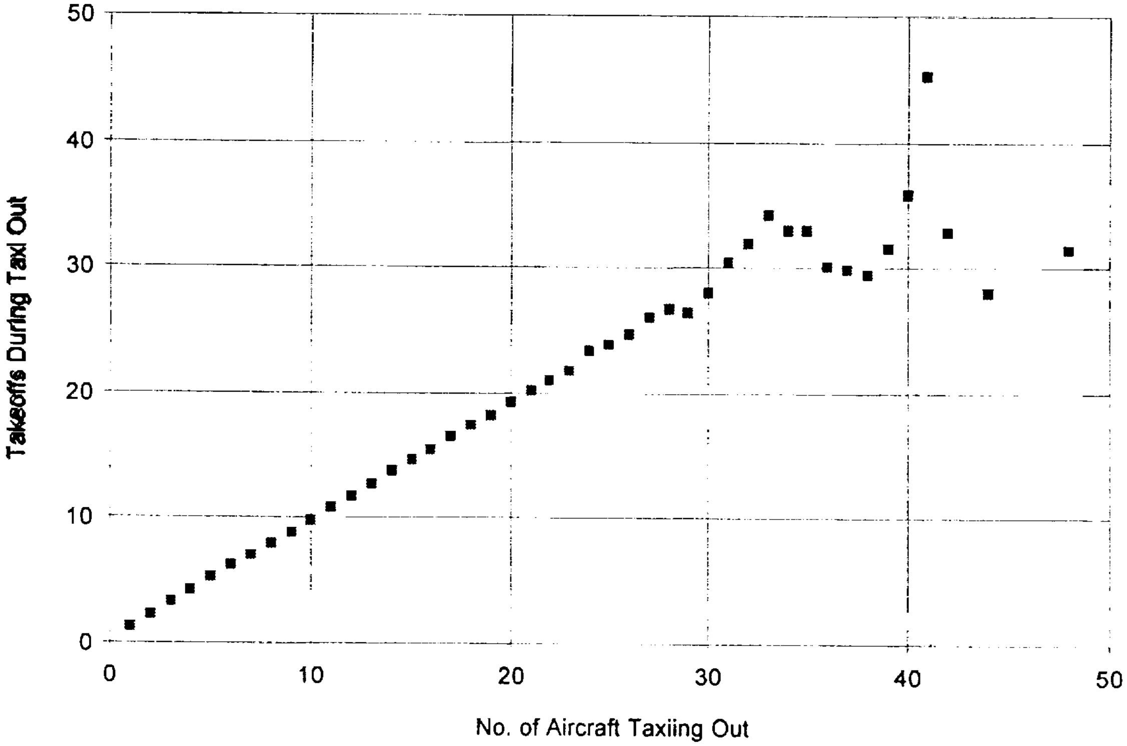

Figure 2: Number of aircraft taking off versus number of aircraft taxiing out

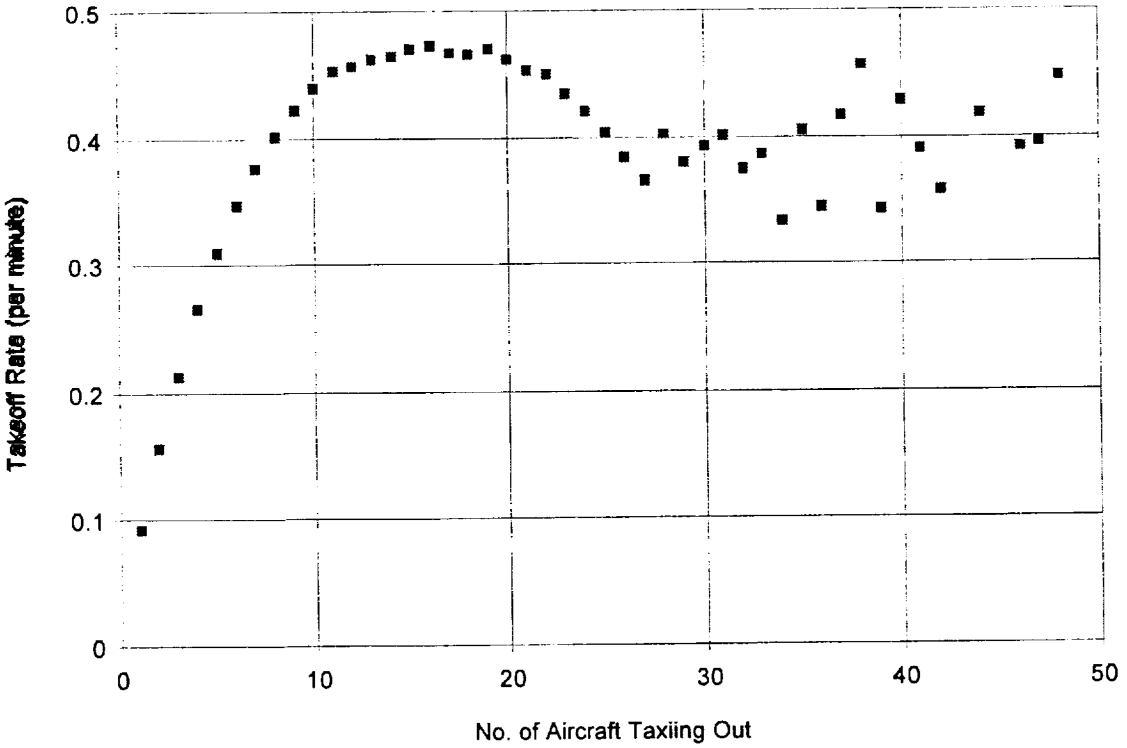

Figure 3: Takeoff rate versus number of aircraft taxiing out

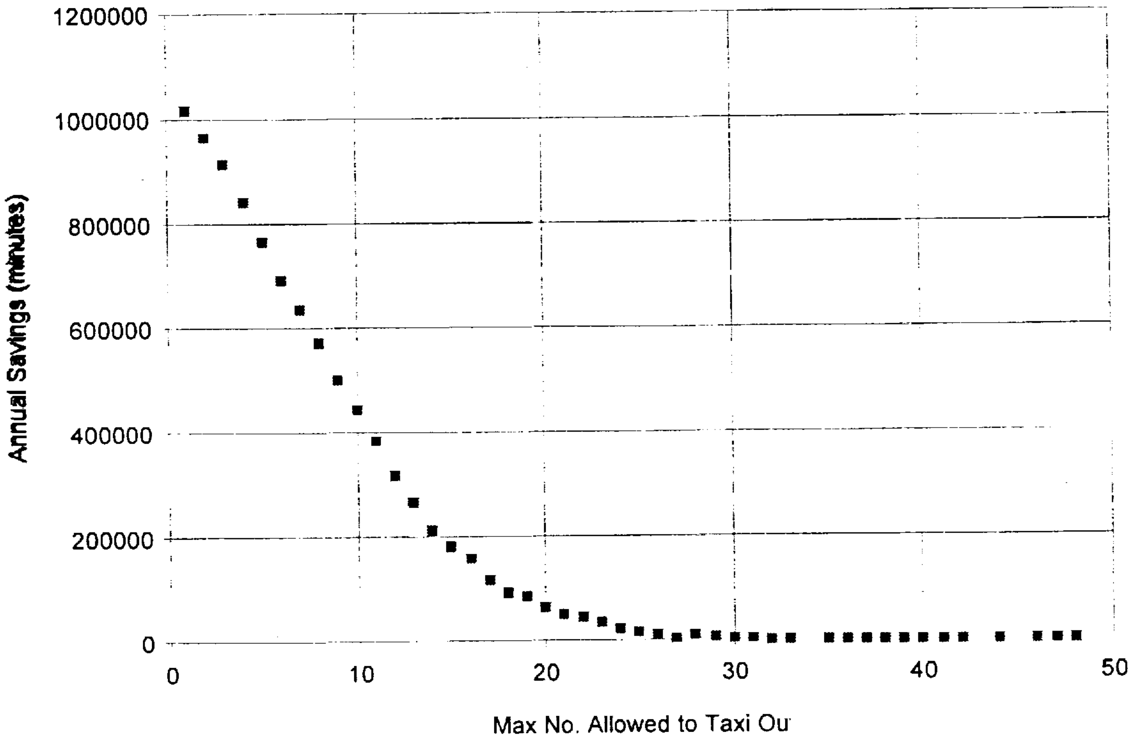

Figure 4: Benefits of N Control versus number of aircraft allowed to taxi out

Table 1: Benefits of N Control at top 40 US airports

Airport	Rank (Operations)	N Control	Benefits (minutes)	Rank (Benefits)
DFW	1	28	83280	5
ORD	2	23	128740	3
ATL	3	25	155900	2
LAX	4	17	6990	22
PHX	5	15	20360	15
DTW	6	20	31176	11
MIA	7	14	3406	28
STL	8	20	56485	9
OAK	9	9	556	44
LAS	10	11	3004	29
MSP	11	17	56840	8
SNA	12	4	30020	12
CLT	13	18	5638	23
BOS	14	10	23335	14
DEN	15	17	36250	10
EWR	16	11	385407	1
SFO	17	15	13238	16
PIT	18	17	11728	17
PHL	19	13	82727	6
CVG	20	16	7660	20
IAH	21	19	26628	13
SEA	22	12	1029	38
SLC	23	14	5386	25
HNL	24	6	5	75
MEM	25	16	5414	24
JFK	26	7	62900	7
LGA	27	10	95542	4
MCO	28	11	8503	19
IAD	29	12	7319	21
PDX	30	14	8	74
DCA	31	12	4762	26
CLE	32	9	11615	18
SJC	34	8	528	45
TPA	35	8	2740	30
BWI	36	9	871	39
MDW	37	6	2684	31
HOU	38	6	2146	32
SAT	39	6	51	63
TUS	40	4	28	70